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Muscular Strength Gains and Sensory Perception Changes; a Comparison of Electrical and Combined Electrical/ Magnetic Stimulation

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ABSTRACT OF THESIS

MUSCULAR STRENGTH GAINS AND SENSORY PERCEPTION CHANGES; A COMPARISON OF ELECTRICAL AND COMBINED ELECTRICAL/MAGNETIC STIMULATION

The purpose of this study was to compare the strengthening effect and sensory perception (pain and perceived contraction intensity) associated with electrical (NMES) and combined electrical/magnetic (PMEF) stimulation on healthy subjects. Subjects were randomly assigned to either a NMES Group (N=21) or a PMEF (N=19) Group. All subjects were blind to group assignment and their opposite limb was used as the control. Subjects completed a familiarization session and were tested the following day to determine the peak torque of the quadriceps femoris muscles of both limbs. The NMES group and PMEF group underwent training that consisted of ten, ten-second induced contractions, repeated three times per week. All subjects completed a McGill Pain Questionnaire (SF) for pain and a 10-cm visual analog scale (VAS) for perceived contraction intensity after the first and last exercise sessions. Eight subjects completed a VAS after every exercise session to determine the reliability of the instrument. The training contraction intensity and maximum current amplitude was recorded for every exercise contraction for all subjects. Testing for peak torque was performed in an identical manner after completion of the four-week training period. The NMES and PMEF Groups demonstrated significant treated limb strength increases of 13% and 17%, respectively. The control limb of both groups demonstrated a 6% strength gain that was significant. The strength gains of the NMES and PMEF Groups were not significantly different from each other nor were the pain intensity and quality rating. The VAS was shown to be reliable with an ICC of R= .95. The PMEF Group perceived their contractions as being more intense ($p < .05$) than the NMES Group. The PMEF Group trained at a significantly higher contraction intensity (70% MVC) than did the NMES group (56% MVC), but no significant difference in the tolerated maximum current amplitude between the Groups was noted.

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(Date)

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MUSCULAR STRENGTH GAINS AND SENSORY PERCEPTION CHANGES; A COMPARISON OF ELECTRICAL AND COMBINED ELECTRICAL/MAGNETIC STIMULATION

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at the University of Kentucky

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THESIS

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CHAPTER 1

INTRODUCTION

Physical therapists have used neuromuscular electrical stimulation (NMES) to strengthen muscle (improve muscle performance, ie torque) and prevent atrophy in patients who are recovering from injury, surgery, or the disuse effects of immobilization. A number of studies have shown NMES to be more effective than voluntary exercise in preventing muscle weakness and atrophy,[1,2] as well as inducing strength gains during the course of rehabilitation.[3-5]

Investigations have also been conducted to assess the ability of NMES to induce strength gains in healthy subjects. While a number of studies show strength induction to be possible,[6-15] none have demonstrated that electrically induced muscle contractions are better than regular exercise for muscle strengthening.[7,10-12,14,15,] A negative aspect of NMES is that it causes pain[16] and cramping sensations[8] when applied at amplitudes required to produce a strengthening effect.

A new device, the MES-10 modified, (MES-10 modified, Cadwell Laboratories, 909 N. Kellogg Street, Kennewick, Washington, 99336) has been developed that induces an electrical current by means of a pulsed magnetic field. Magnetic stimulation can produce strong muscle contractions in healthy subjects but does so with great variability.

Torque values ranging from 8 to 82% of healthy subjects' maximal voluntary contraction have been elicited with the magnetic stimulator.[17] Unlike conventional NMES, however, muscle contractions elicited by magnetic stimulation produce relatively little or no pain. The electrical current induced by magnetic stimulation occurs deep within the tissue stimulated and is undiminished by skin impedance.[18] As a result, large diameter motor nerve fibers are stimulated while the smaller diameter pain fibers are not.[19] When conventional NMES is combined with magnetic stimulation an augmented response occurs. Subjects receiving combined electrical/magnetic stimulation (PMEF) produce a stronger muscle contraction that is less painful compared with subjects receiving conventional NMES alone.[17,20] The limited research conducted to date, however, has not shown magnetic stimulation alone to be effective in producing strength gains in healthy subjects or patients recovering from surgery.[21,22] There has only been one study to date comparing conventional NMES to PMEF. Currier et al. found that PMEF was equally effective as conventional NMES in reducing limb atrophy, while both groups demonstrated significant strength gains from pretest levels when tested six weeks after surgery.[22] Combining NMES with magnetic stimulation may produce greater strength gains with less pain than is achieved by NMES alone.

Statement of the Problem and Hypotheses

The problem addressed by this study was to see if a method existed for producing strength gains in healthy subjects that is less painful than NMES. The null hypotheses are that: 1) NMES and combined (NMES and magnetic) stimulation produce equivalent strengthening effects. 2) Subjects receiving NMES and combined stimulation experience equivalent levels of pain and perceived contraction intensity. The alternative hypotheses are: 1) PMEF produces greater strength gains than NMES alone. 2) Subjects receiving PMEF experience less discomfort than subjects receiving NMES alone.

Purpose

The purpose of this study was to compare the strengthening effect and sensory perception changes (pain and perceived contraction intensity) associated with NMES and PMEF. The results of this comparison will benefit the medical community by: 1) Determining the ability of PMEF to produce strength gains in normal subjects. 2) Determining if PMEF causes less discomfort than NMES. Should PMEF produce greater strength gains with less discomfort than the current state-of-the-art method of involuntary muscle strengthening (NMES), clinicians may be able to offer patients a more efficacious rehabilitation program.

Scope of the Study

This research, conducted from September 1991 through November 1991, compared two forms of stimulation used to

induce involuntary muscle contractions, NMES and PMEF. Changes in torque, pain perception, and perceived contraction intensity were the measured outcomes. A sample of convenience was obtained from undergraduate physical therapy students, University staff, and students enrolled in the University's ROTC (Reserve Officer Training Corps) program. Data were gathered on 40 healthy male and female volunteers who were randomly assigned to one of two treatment groups - NMES or PMEF. All subjects were required to read and sign a consent form (Appendix A) before starting. Subjects were free to withdraw from the study at any time without penalty. A Cybex II dynamometer (CYBEX, Division of Lumex, Inc, 2100 Smithtown Ave, Ronkonkoma, NY 11779) was used to record pre-test torque measurements on both limbs of all subjects. All subjects participated in a practice session conducted the day prior to the pre-test measurement. This practice session was conducted to eliminate torque gains due to familiarization. Both Groups participated in exercise sessions conducted three times a week over a four-week period with the subjects' dominant limb receiving the treatment stimulus. The opposite limb of each subject was used as the Control Group. Limb dominance was determined by having subjects kick a ball. The limb used to kick the ball was designated the dominant limb. Post-test measurements were taken in the same manner as pre-test measurements. Subjects completed a McGill Pain Questionnaire (short form) and 10-cm visual analog

scale (VAS) for perceived contraction intensity at the end of the first and last exercise sessions. In addition, four randomly chosen subjects from each group completed VAS pain scale after each each exercise session. This VAS was administered to determine the reliability of the 10-cm visual analog scale when measuring pain caused by electrical stimulation over repeated applications. The stimulus amplitude and torque values were recorded for all 120 exercise contractions. All data collection, exercise sessions, and testing took place in the Division of Physical Therapy Research Laboratory, University of Kentucky, Lexington, Kentucky.

Variables

The independent variables in this study were: 1) NMES and PMEF stimulation; 2) duration of stimulation; and 3) number of exercise contractions; 4) number of exercise sessions. The dependent variables in this study were: 1) muscle torque produced; 2) pain level experienced; and 3) perceived contraction intensity.

Definition of Terms

Maximal voluntary isometric contraction - the highest isometric torque generated by the quadriceps femoris muscle from three maximal voluntary isometric contractions; each contraction lasting five seconds and separated by a two-minute rest period.

Training contraction intensity - Amount of isometric torque produced by the quadriceps femoris muscle during

treatment expressed as a percentage of the maximal voluntary isometric contraction.

Dominant limb - the limb employed by the subject when asked to kick a stationary ball.

Exercise contraction - one period of NMES or PMEF consisting of ten seconds of stimulus and fifty seconds of rest, numbered 1 through 120.

Exercise session - a set of ten exercise contractions, numbered one through twelve.

Stimulus timing - the amount of time the stimulation is ON to the amount of time the stimulation is OFF.

Pain - the individual subject's perception of the unpleasantness associated with the stimulation induced muscle contractions.

Perceived contraction intensity - the subjects perception of muscle contraction intensity produced by stimulation compared to the intensity of a voluntary contraction.

Limitations

Limitations in this study include:

Subjects will provide maximal effort during pre-test torque measurements

Subjects may vary their level of activity during the course of the study.

Subjects will attend all exercise sessions.

Subjects will allow stimulation to their maximum tolerable limit each exercise contraction.

Chapter 2

LITERATURE REVIEW

Neuromuscular electrical stimulation (NMES) has been used by physical therapists for improving muscle strength in both normal subjects and patients recovering from surgery or trauma. A new device has been produced that, like NMES, is capable of inducing muscle contractions by means of a time-varying (pulsed) magnetic field. A review of past work establishing the efficacy of NMES in muscle strengthening is presented. The history of magnetism, principles of magnetic stimulation, and current clinical application of pulsed magnetic fields is also reviewed. These reviews will provide a theoretical basis for evaluating the concept and efficacy of induced muscle strengthening via electrical stimulation and pulsed magnetic stimulation.

Effect of Neuromuscular Electrical Stimulation on Muscle Contraction and Muscle Fiber Type

When applied to normally innervated musculature, NMES elicits a muscle contraction by depolarizing the motor nerve and its branches innervating the targeted muscle.[23] Contractions induced by NMES differ from those elicited volitionally. NMES induced contractions cause synchronous depolarization of motor units in contrast to the

asynchronous pattern that occurs with voluntary contractions.[24,25] As a result, NMES causes muscle fatigue to occur more rapidly than does normal exercise.[26]

Neuromuscular electrical stimulation appears to selectively activate fast twitch, glycolitic muscle fibers (type II) first and then slow twitch, oxidative fibers (type I). Voluntary muscle contractions recruit muscle fibers in the opposite manner, with type II fibers being added as muscle tension increases.[27,28] Type II fibers are innervated by large diameter nerves and are more easily depolarized by NMES than the smaller diameter nerves that innervate type I fibers. This altered recruitment pattern in response to NMES has been shown to occur in animals[29,30] and evidence suggests that it occurs in humans as well.[31,32] Prolonged application of NMES (> 3 weeks) has also demonstrated the ability to convert type II fibers to type I fibers,[33,34,35] though these ultrastructural effects on muscle are fully reversed six weeks after stimulation is discontinued.[33]

The ultrastructural effects NMES produces in skeletal muscle have important clinical implications; patients recovering from the effects of disuse atrophy secondary to immobilization show a selective decrease in type I fiber area and a diminished concentration of oxidative enzymes.[36,37] Studies applying NMES to muscle during immobilization have demonstrated that a reduction in succinate dehydrogenase[2] and ATPase levels[38] is prevented.

Neuromuscular Electrical Stimulation as a Muscle Strengthening Technique

Electrically induced muscle contractions have been employed in healthy subjects in an attempt to increase muscle strength.[6-15,39] Muscle strength is the ability to produce torque (force). Although research investigating NMES induced strength gains was reported in 1965,[39] only investigations conducted over the past 12 years attempting to reproduce results reported by Kots have gained the attention of researchers and clinicians.[26] In 1976, Kots reported using a 2,500 Hz NMES device to induce rapid strength gains of 30 to 40% in highly trained athletes. Kots theorized that NMES activated a greater number of motor units than was achieved by voluntary contraction and thus resulted in greater adaptive changes (ie. strength). He stated the current used to obtain his remarkable results utilized a 2,500 Hz carrier frequency signal modulated by bursts which had an anesthetizing effect on the muscle stimulated. Therefore, subjects experienced less pain than when stimulated at slower frequencies and were able to tolerate higher current amplitudes. Subsequent investigators, while producing strength gains in healthy volunteers, have been unable to reproduce his results.[40] The inability of researchers to reproduce the results of

Kot's work may be due either to his inadequate description of his methodology or reporting exaggerated results.

Controlled trials have not substantiated the theory that NMES induced muscle contractions recruit more motor units than voluntary contractions.[41-44] Several subjects in one NMES training study did, however, acheive NMES induced contractions that were greater than 100 percent of their maximal voluntary isometric contraction. While the intensity of contractions greater than 100 percent MVC ranged from 109% to 165%, it most likely overestimates the true percentage of one's MVC achieved. The pretest MVC was used to compute the contraction intensity, while the true MCV was probably increasing during the course of training.[9] These results highlight the fact that there is a wide variation of response by subjects to NMES.

Locicero superimposed NMES (delivered at 2,500 Hz carrier frequency and modulated to 50 bursts per second) on maximal voluntary contractions (MVC) of the knee extensor muscles which generated torque values in subjects ranging from 93 to 104% of their MVC. He demonstrated this in both isometric and isokinetic modes but did not induce torque that was significantly greater than that acheived by voluntary contractions.[41] Other investigations utilized various frequencies and waveforms to compare the torque production of contractions produced by NMES only, volitional effort, and superimposed NMES and volitional effort.[42-44] While some subjects perceive NMES induced contractions as

more intense than voluntary contractions,[43] no method has produced more torque than volitional effort alone; in some cases significantly less.[42,43]

Pain appears to be a limiting factor when using NMES to induce strength gains. However, most subjects adapt to the pain over time which allows the stimulus amplitude to be progressively increased.[16] Investigators have attempted to decrease pain perception by varying the burst mode and carrier frequency,[45] employing different waveforms,[46] and application of electrical stimulation at sensory levels prior to NMES.[47] Although these methods are effective to a degree, subject response is variable and pain is still experienced with high amplitude stimulation.

Comparing the results of studies that have evaluated NMES's ability to induce strength gains in muscle is difficult because of the number of confounding factors. Different muscles, including all major muscle groups of the upper extremity,[39] abductor digiti quinti,[48] and quadriceps femoris[6-15] have been the target of NMES strengthening regimens. The quadriceps femoris muscle has been studied most frequently. These functionally different muscle groups may respond and adapt differently to NMES induced muscle contractions. Muscle length-tension relation, an important factor in force development,[49] has not always been taken into account. Although maximum isometric knee extension torque has been shown to occur with hip and knee angles at 60 degrees,[50,51] a variety of trials report isometrically

testing and exercising subjects at different joint positions. These joint positions vary from 30^0,[8,12] 45^0,[7,15] and 90^0 [14] at the knee and 70^0,[13,9] 80^0, [8] and 90^0, [7,14] at the hip. Although these trials show NMES alone or NMES combined with voluntary exercise to be an effective means of increasing isometric and isokinetic muscle strength in normal subjects, they have not shown NMES to be more effective than voluntary exercise.[6-15, 39,48,49]

NMES trials effective in producing strength gains in normal subjects demonstrate a variety of stimulus characteristics and training regimens: frequencies ranging from 33 to 2000 pps; amplitudes of 30 to 80 mA and 100 to 400 V; waveforms of trapezoid, rectangular, surging, sine, and biphasic configurations;[26] inducing 100[6] to 250[11] total contractions over a period of three[12] to six[7] weeks; and using the subjects tolerance[7-9,13-15] or a predetermined percentage of MVC[6,10,12] to guide stimulus amplitude. Reported mean training contraction intensities successful in inducing strength gains range from 33[11] to 91[9] % MVC. Soo and associates, in an attempt to maximize the efficiency of an NMES regimen, found two sessions weekly for five weeks at a stimulus amplitude producing 50% of MVC adequate to induce strength gains in males.[6] Only Boutelle has assessed strength retention after discontinuation of a NMES strengthening program. The Electrical Stimulation Group demonstrated a 32% increase in isometric strength at posttest. One month later subjects were retested and

produced a mean torque value still 28% greater than their original mean pretest torque value.[8] Currier and Mann[10] and Selkowitz[9] showed strength gains to be correlated with increased training contraction intensity (ratio of exercise contraction/MVC).

Currier states that stimulus amplitude, frequency, and pulse duration are the most important factors in successfully inducing NMES strength gains, as opposed to waveform and types of stimulating devices.[26] Studies have been reported which found NMES induced strength gains, though showing a positive trend, to be statistically insignificant.[39,52] These results may be due to technological limitations of the waveform stimulus[39] or small sample sizes resulting from multiple group divisions of the total sample.[52]

Work using NMES to induce strength gains in the clinical setting also has been reported. The results from studies involving patients with chondromalacia patella,[5] recovering from ACL reconstruction,[2,3,53] and the effects of immobilization due to trauma[54] are more uniform and dramatic than those involving healthy subjects.

Treating a series of 50 patients having chondromalacia patellae, Johnson and associates reported NMES induced strength gains of the quadriceps femoris muscle to be superior over voluntary isometric exercise. Patient improvement ranged from 25% to 200% of pretreatment strength values.[5] Godfrey et al conducted a double-blind clinical

trial involving 35 patients recovering from surgery or trauma that compared NMES to voluntary isometric exercise. Subjects showed a significant strength increase when tested isokinetically at 3 rpm but not at faster speeds of 10 and 25 rpms.[4] Both Johnson et al and Godfrey et al noted that strength gains were more pronounced in weaker patients. Erikkson and Haagmark treated patients recovering from ACL reconstruction with NMES and found they exhibited improved strength levels, less atrophy, and a higher succinate dehydrogenase level when compared to the control group who did not receive NMES. A subjective method of assessing strength gains was used which prevented comparing the magnitude of change between the patients and controls.[2] Delitto et al also reported NMES to be a more effective means of inducing strength gains of quadriceps femoris and hamstring musculature in ACL patients than voluntary exercise the first six weeks after surgery.[3,53] Gould and associates treated patients recovering from open menisectomy with a portable NMES unit that utilized a monophasic square wave delivered at 35 pulses per second. The treatment regimen consisted of five-second contractions elicited 400 times a day. Patients receiving NMES demonstrated significantly less muscle atrophy, strength loss, and joint effusion than the voluntary exercise control group. Duration of crutch use, amount and type of medication used, and knee joint range-of-motion were other outcome measures which the stimulated group differed significantly from the

control group.[1] Nitz and Dobner reported a case in which NMES elicited co-contractions of an athlete's quadriceps femoris and hamstring musculature during three weeks of immobilization therapy for a grade II medial collateral ligament sprain. At the end of the three-week period, the affected limb demonstrated a 1.5 cm quadriceps femoris muscle hypertrophy, trace level of knee effusion, and single-leg, vertical leap height was 92% of the uninjured leg. No quantitative strength values were reported other than a normal manual muscle grade for both quadriceps femoris and hamstring muscle groups of the treated limb.[54]

As with studies involving healthy subjects, research using NMES to induce involuntary muscle contractions in unhealthy subjects uses a variety of stimulus characteristics and treatment regimens. Most reported using subject tolerance to quide stimulus amplitude and administer exercise sessions daily[1,2,4,53,54] or every other day.[5]

History of Magnetic Stimulation

Man has long known of the existence of magnetism. Greek writings that date back to 800 B. C. mention magnetite (loadstone), a mineral which produces a magnetic field.[55] While magnets were being used as therapeutic tools in the 17th century, Gilbert, a physician, was the first to clearly differentiate the role of electricity from magnetism in his 1600 treatise "De Magnet".[17] In 1831, Faraday discovered

that an electrical current was produced in a circuit subjected to a changing magnetic field (electromagnetic induction). The Danish physicist found the opposite to be true as well. In 1836, Oersted found that when an electric current passed through a conductor, a magnetic field or flux was created around the conductor. At the end of the 19th century d'Arsenoval used an electric coil to produce a time varying magnetic field and reported the production of magnetophosphenes (flashes of light produced in the retina) and vertigo in subjects. Tompson (1910), Dunlap (1911), and Magnusson and Stevens (1914) later reproduced and verified d'Arsenoval's findings.[55]

Magnetic therapy was used in the early part of this century to treat anaemia, arteriosclerosis, chorea, convulsions, hysteria, insomnia, migraine, neuralgia, neurasthenia, neuritis, and rheumatism.[56] Hansen, in a series of case reports published in 1938, reported the influence of magnetism on pain. Both magnets and electromagnets were used to treat patients with a wide variety of disorders and pain was reported to diminish in most cases.[57] Kolin and co-workers were the first to report the use of a magnetic field to stimulate peripheral nerves. They produced a muscular contraction in a frog muscle/nerve preparation by winding it around an electromagnet that produced a changing magnetic field of 60 to 100pps.[58] Bickford and Fremming introduced a device in 1965 that used electric current to create a time varying (pulsed) magnetic

field that was capable of stimulating peripheral nerves in humans. The design of their machine and technological limitations did not allow it to be used for clinical research; sparks and smoke were produced each time the unit was discharged.[59] Work began in 1977 in England to overcome the technical problems associated with magnetic stimulation devices.[60] As a result, a stimulator was developed in 1982 that was use to depolarize the median nerve of a human subject and the resulting compound muscle action potential was recorded.[61] The success of stimulating a human nerve led to the manufacturing of magnetic stimulators in 1985.[60] Since then, research using time-varying magnetic fields has been conducted in the area of pain control,[62-64] neural conduction studies,[20,65,66] and muscle strengthening.[21,22] Magnetic fields are also used in medicine for diagnostic imaging of body parts (Magnetic Resonance Imaging), cortical mapping,[17] directing catheters through the circulatory system, and removing small pieces of iron from the eye.[67]

Principles of Magnetic Stimulation

The purpose of magnetic stimulation is to create an induced electrical current in order to depolarize nervous tissue. The field must be time varied, or pulsed, for depolarization to occur.[18] Magnetic stimulators accomplish this by passing electrical current through a coil which in turn creates a pulsed magnetic field. The amplitude of the

magnetic field, or flux density, is measured in teslas (T) or gauss (g) (10,000 g = 1 T). The pulsed magnetic field in turn, produces an induced electrical field within the field.[60] This effect is in accordance with Faraday's law which states that whenever a magnetic field changes there is an induced electrical field which impedes the changing magnetic field.[18] The magnitude of the electrical field induced is expressed by the formula: $E = \frac{dB}{dt} \times \frac{r}{2}$

E is the amplitude of the electrical field, d/B is the rate of change of the magnetic field, and r is the radius of the circular loop (stimulation coil). This formula shows that increasing the magnetic field's rate of change and the size of the stimulating coil will increase the magnitude of the electrical field induced around the coil.[65] If a conducting medium such as human tissue lies within the induced electrical field, current will flow through the tissue as a cosine waveform but in the opposite direction of current flowing through the coil. If the induced current density is of sufficient amplitude and duration, neuromuscular tissue will be depolarized the same way as if electrodes had been used to transmit the current.[18]

Nervous tissue does not respond to the magnetic field itself but rather to the induced electrical current created by it. This situation has led Geddes to suggest that magnetic stimulation is a misnomer and that "electrodeless electric stimulation" is a more accurate descriptor.[19]

An electromagnetic coil acts as an electrode to generate the magnetic field, producing in turn an induced electric current.[68] Several factors concerning coil electrode application need to be considered: 1) the amplitude of the induced electric field is minimal in the center of the coil and greatest under the edges; 2) the amplitude of the induced current diminishes as its distance from the coil increases; 3) the functional anode and cathode are within a few millimeters of each other (reversing direction of the coil does not affect latency times); 4) an orthogonal-longitudnal coil placement is most effective in eliciting a motor response. 5) pushing the stimulating coil against the nerve stimulated allows response maximization. Placing the coil electrode in a transverse orientation allows greater stimulus localization but requires greater amplitudes to obtain the same response elicited with orthogonal-longitudnal coil placement.[66] Tufts confirmed this by using a computer to calculate the spatial distribution of currents induced by coils and found that current density is decreased when the coil is placed in a perpendicular orientation relative to the body part stimulated.[69]

Magnetic stimulation has several advantages and disadvantages when compared to electrical stimulation. Advantages are: 1) the induced electrical current is not attenuated by body tissue (even high resistance structures such as bone); 2) the ability to stimulate deep structure

such as the brain, brachial plexus, and lumbar roots with little or no pain; 3) physical contact with the body is not required, allowing stimulation to be applied directly over clothing and moved easily about for optimal stimulation. Disadvantages are: 1) stimulation units are heavy and bulky; 2) the site of stimulation is not well defined; 3) stimulation at rapid rates causes the stimulation coil to heat.[60]

Current Clinical Applications of Magnetic Stimulation

Hansen published a series of case reports in 1938 describing the treatment of patients with sciatica and low back pain in which magnets and electromagnets effected significant pain relief.[57] A number of reports have appeared in the literature since then which use magnetic fields to relieve pain. Nakagawa reported that significant improvement occurred in patients suffering from shoulder, neck, back, and chest pain of unknown origin as well as headaches and constipation when treated with a magnetic necklace that produced a magnetic field intensity of 700 to 1300 gauss.[62] Hong and associates attempted to reproduce his results in patients with chronic neck and shoulder pain using the magnetic necklace and employed sham treatment as well. The majority of subjects reported subjective improvement, indicating a significant placebo effect. They also applied the necklace to a control group of asymptomatic

individuals and subsequently measured a significant decrease in nerve conduction velocity. They believed that the field density employed altered the conduction of larger mixed nerves while not affecting the smaller nociceptive fibers.[63] Trentin and Visentin applied low-amplitude (200 to 600 gauss) magnetic stimulation to patients suffering from rheumatoid and osteoarthritis with mixed results. The osteoarthritis group had pain and range of motion changes they classified as "good", but were limited to only four months.[64] Binder and co-workers, prompted by encouraging results from a pilot study, conducted a controlled, double blind trial using a pulsed magnetic field to treat patients with rotator cuff tendonitis of greater than 3 months duration. At the end of the eight-week trial, significant improvements in pain level, range of motion, and response to resisted shoulder movements were noted. They did not report the field density employed.[70] Lunt and Barker also report successful results treating rotator cuff tendonitis with a magnetic field strength of 20 to 60 gauss.[71]

Warnke has proposed that three factors that may be involved when low-amplitude magnetic stimulation is used to reduce pain: 1) the widening of blood vessels due to autonomic nervous system activity; 2) the increased partial oxygen pressure in tissue; and 3) the change in local profusion and velocity of capillary blood flow.[72]

Magnetic stimulation has been used extensively to perform neural conduction studies of both the central and

peripheral nervous system.[73] The first clinical trial using magnetic stimulation to study central and peripheral conduction times was conducted by Barker and associates in 1986. Comparing normals, patients with multiple sclerosis, and patients with lower motor neuron disease, they found that the multiple sclerosis group exhibited increased cortex to spine latencies.[65] Hess and coworkers later confirmed these findings when comparing patients with multiple sclerosis to healthy subjects.[74] Bickford and co-workers, interested in the effects of combined stimulation (PMEF), applied conventional electric stimulation, magnetic stimulation, then PMEF stimulation to the ulnar nerve. They observed an enhanced response that ranged from 2 to 4 times the combined amplitude of electrical and magnetic stimulation applied separately.[20] Intracranial stimulation of the facial nerve has been reported by several investigators.[75-77] Metson and his group stated that their subjects experienced no pain during stimulation and obtained latency values within the standardized normal range for electrical stimulation. They concluded magnetic stimulation was a useful technique in the diagnosis and treatment of facial nerve disorders.[77]

Evans and associates, however, point out several problems associated with the use of magnetic stimulation in conducting peripheral nerve evaluations. First, the precise point of nerve depolarization is not known and precludes accurate measurement of nerve segments to calculate

velocities.[78] Inability to determine the point of nerve depolarization has been noted as a problem by other investigators, as well.[79,80] Secondly, they were rarely able to obtain supramaximal activation of the median nerve at the wrist without overflow occurring in the ulnar nerve, thereby distorting the recorded compound muscle action potential. This prevents an accurate assessment of the alpha motorneuron population available for conduction as well as selective nerve stimulation, both being important factors in electrophysiological studies. They concluded that until improvements in current coil design and stimulator power were overcome, magnetic stimulation is not suitable for use in routine peripheral nerve conduction studies.[78]

Geddes cites Hallgrens work of 1973 as the first report using a pulsed magnetic field to induce tetanic muscle contractions in both humans and animals. Hallgren was able to deliver stimuli with frequencies up to 125pps, but the coil became extremely hot after about 1 minute and required cooling before continued use.[81]

The MES-10 is a prototype magnetic device developed by Cadwell Laboratories for investigational use as a muscle stimulator. It produces a maximum field density of 1.5 T and induces current in tissue at a rate 60 pps with a cosine waveform. Two research projects and several pilot studies conducted at the University of Kentucky have investigated this unit's ability to provide high level muscle

contractions. In 1989, Currier, Kellogg, and Nitz found the MES-10 was able to induce a contraction of the thigh muscles ranging from 8 to 82% of their MVC in 20 healthy volunteers. Kellogg later combined NMES with magnetic stimulation and observed an augmentation effect, thereby confirming Bickfords et al's report of response enhancement. Ten subjects received NMES of 2,500 Hz modulated at 50 bursts per second to the quadriceps femoris muscle. Magnetic stimulation was simultaneously applied with the magnetic coil placed over the NMES electrodes. Subjects tolerated an average contraction intensity of 51% MVC when electrical stimulation alone was applied. Magnetic stimulation alone applied at maximal output was well tolerated by all subjects but only elicited an average contraction intensity of 44% MVC because of limited device output. Applying the two types of stimulation simultaneously resulted in an average contraction intensity of 65% MVC. Of major significance is the fact that all subjects reported the combined stimulation to be less painful than electrical stimulation alone.[17] Kellogg also compared the affect of conventional electrical stimulation and magnetic stimulation on strength and sensory perception changes. Neither group demonstrated any statistically significant strength gains. However, perceived pain level and contraction intensity were significantly lower for the group receiving magnetic stimulation.[21] Because all subjects achieved the magnetic stimulator's maximum output within the first week, it is

unclear whether the increased comfort was a result of the magnetic stimulation or a result of amplitude limitations of the stimulator. Currier and associates conducted a study which used conventional NMES and PMEF stimulation to reduce loss of thigh girth in patients recovering from ACL ligament reconstruction. Patients receiving PMEF had less thigh girth loss than controls and torque loss was reduced with combined stimulation after six-weeks of treatment. Patients in the combined stimulation group experienced 50% less pain than those who received only electrical stimulation, as measured by the 10-cm visual analog scale.[22]

No safety problems or side effects resulting from to the use of magnetic stimulation have been reported.[68] Pascual-Leone and coworkers have reported that one subject received a burn under a siver/silver-silver chloride EEG electrode during rapid rate transcranial stimulation. They concluded that this burn was the result of heating and skin contact of the electrode. The type of electrode material used in association with magnetic stimulation is a consideration if it lies within the magnetic field.[82]

Summary

Research to date shows that muscle contractions induced by magnetic stimulation are less painful than contractions induced by electrical stimulation. Combining both types of stimulation appears to augment muscle contraction force.

Magnetic stimulation alone has not been shown effective in producing strength gains in healty subjects because of device limitations but when used in combination with NMES it has reduced girth loss in post-surgical patients. If combined electrical/magnetic stimulation is shown to be less painful during application and produce a strengthening effect in healthy volunteers, it could be a useful tool in patient rehabilitation.

CHAPTER 3

METHOD

This chapter describes the subjects, methodology, and statistical analysis used in this study. This study compared the effect of conventional NMES and PMEF on knee extension torque, pain, and perceived muscle contraction intensity.

Subjects

All subjects were recruited from colleges on the University of Kentucky campus. A total of 40 subjects, 18 male and 22 female volunteers, between the ages of 18 and 37 years completed this research project. Table 1 presents the descriptive statistics for the subjects' age, height, and weight. Two subjects in each group were lost because of knee or thigh pain. Two subjects in the PMEF group were unable to achieve an induced contraction of at least 30% of their MVC and were eliminated from the study. All subjects were in a good state of health, had no prior history of knee surgery or current lower limb pathology, and had no nervous system disease. Females who were pregnant and individuals with metallic implants or biomedical devices (cardiac pacemakers or choclear implants) did not participate. An explanation of the purpose of this research project and its

Table 1

Subject Demographic Data

	Group					
	NMES			PMEF		
	M	F	Total	M	F	Total
Age (years)						
$\bar{X}$	26.9	23.9	25.2	26.1	24.2	25.1
SD	7.5	5.2	6.3	5.12	4.8	5.1
Min	19	20	19	19	20	19
Max	37	35	37	34	32	34
Height (cm)						
$\bar{X}$	179.8	164.5	171.0	180.3	163.8	171.7
SD	5.9	5.9	9.7	6.6	6.4	10.9
Min	170.2	154.9	154.9	170.2	152.4	152.4
Max	188.0	175.3	188.0	188.0	177.8	188.0
Weight (kg)						
$\bar{X}$	82.5	57.8	68.4	76.8	56.6	66.1
SD	9.8	6.2	14.6	4.8	10.8	13.7
Min	65.8	48.5	48.5	71.7	45.4	45.4
Max	93.0	68.0	92.9	86.2	83.9	86.2

objectives was given to all subjects. They were then asked to read and sign the informed consent document (see Appendix A) which was approved by the Internal Review Board of the University of Kentucky. This document explains the role of the subject, possible risks and benefits, and details the subject's rights.

Description of Data Collection Methods

Experimental Design

A single-blind, pretest/postest design with repeated measures was used for this study. All subjects (N=40) were randomly assigned to either the NMES Group (N=21) or the PMEF (N=19) Group. Assignment randomization was done by using a random numbers table. The opposite leg of all subjects comprised the Control Group.

Instrumentation and Facilities

All testing, exercise sessions, and data recording were completed in the Division of Physical Therapy Research Laboratory, University of Kentucky, Lexington, Kentucky.

A Cybex II isokinetic dynamometer (CYBEX, Division of Lumex, Inc, 2100 Smithtown Ave, Ronkonkoma, NY 11779) was used to measure all subjects quadriceps femoris muscle torque. Measurements were taken in an isometric mode by using a speed setting of 0^0 per second. Torque values were recorded on a strip chart with a damp setting of two.[83] The interrater and intrarater reliability of the Cybex II has been previously established by other investigators.[84]

The Electrostim 180-2i (Elecrostim USA LTD, PO Box 3425 Joliet, Illinois, 60435) was used to provide the electrical stimuli applied to subjects in this study. The stimuli consisted of 0.1 msec sinewaves at a carrier frequency of 2,500 Hz and delivered at 50 bursts per second. Two electrodes (bipolar technique) were used to apply the

electrical current which was adjusted to the subjects' maximum tolerance.

The MES-10 modified magnetic stimulator equipped with the large diameter coil (26 cm diameter) was used to induce an electrical current flow in the subjects tissues. The coil was applied over the NMES electrodes in both the NMES and PMEF Groups but was only activated for PMEF subjects. The device produced a cosine waveform pulse duration of 240 microseconds, with a rise time of 30 microseconds. This stimulus was repeated at 60 pps.

The ten-cm visual analog scale (see Appendix B) was used to measure subjects' perceived contraction intensity. Scott and Huskisson have indicated that the scale is valid and reliable as a measuring tool.[85]

The McGill Pain Questionnaire (short form, see Appendix B) was used to measure the subjects' pain level. This questionaire contains three parts. Part 1 consists of 15 words representing three qualities of pain: sensory; affective (emotional, autonomic); and evaluative (overall intensity). Part 2 consists of a five-point interval scale which measures the overall pain experience and ranges from "mild" to "excruciating". Part 3 is a 10-cm visual analog scale that measures pain intensity, ranging from no pain to the worst possible pain.

Tests

The dominant limb of all subjects was identified by having them kick a stationary ball on the floor. The limb

used to kick the ball was identified as the dominant limb. Treatment was applied to the dominant limb of all subjects and their nondominant limbs comprised the Control Group.

Practice Procedure

Familiarization sessions using the Cybex II dynamometer were conducted on both limbs the day prior to the pretest procedure. In addition to performing voluntary contractions, the dominant limb also received electrical stimulation contractions. These sessions were administered to prevent any torque changes that may occur due to lack of familiarity with the equipment or training procedure, and to decrease any apprehension of induced stimulation.

Beginning with the nondominant limb, subjects were seated on the Cybex II chair with the hip angle positioned at 60^0 of flexion and the dynamometer's axis of rotation was aligned with the anatomical axis of the knee. The moment arm of the Cybex was then adjusted to each subject's leg and secured by a web strap; web straps were also placed across the subject's waist and thigh. The moment arm was then positioned so that the subject's knee was in 60^0 of flexion and the Cybex was set at a speed of 0^0 per second.[50,51] The opposite limb was allowed to hang over the edge of the table unrestrained and subjects were instructed to hold the handgrips on the side of the seat. Subjects then performed three consecutive submaximum isometric quadriceps femoris muscle contractions held for two seconds each. A one-minute rest interval followed this warm-up period. Three maximum

voluntary isometric knee extensor muscle contractions were then performed, each lasting five seconds and separated by two-minute rest intervals. During the contraction phase all subjects were given maximum verbal encouragement.

Upon completion of the familiarization session for the nondominant limb's, two carbon rubber electrodes (8 x 12.5 cm) were applied to the subjects knee extensor muscles of the dominant limb. The electrodes were then connected to the Electrostim 180-2i and the subject's dominant limb was secured to the Cybex II as previously described. Exercise of the dominant limb was then accomplished in the same manner as for the nondominant limb. A two-minute rest period followed the last maximal voluntary muscle contraction and each subject then underwent three NMES induced involuntary muscle contractions. Each contraction lasted five seconds, was separated by a 50 second rest interval, and stimulus amplitude manually adjusted to the subjects' maximum tolerable level.

Test Procedure

The Cybex II dynamometer was used to determine the maximum voluntary isometric knee extensor torque of both limbs of each subject prior to initiating the experimental exercise sessions. The testing sequence was reversed but the position and procedure used for testing maximum knee torque was identical to the one used during the practice session described previously. All subjects participated in a warm-up session prior to testing which was also identical

to the one described in the practice procedure. Subjects were then instructed to extend their knee with as much force as possible and maintain the effort until instructed to relax (5 seconds). Three contractions were performed with two-minute rest intervals between contractions. Torque was recorded by a dual channel recorder (damp setting =2) during each of the three voluntary contractions. The highest peak torque score of the three trials was used as the subject's MVC pretest score. The maximum voluntary isometric quadriceps femoris muscle torque of both limbs were tested upon completion of the experimental exercise sessions. This procedure was identical to the pretest procedure conducted prior to the initiation of experimental exercise sessions. Once subjects achieved an induced muscle contraction equaling 30% of their pretest MVC, they were administered the 10-cm visual analog scale for perceived contraction intensity and a short form McGill Pain Questionaire. These instruments were re-administered after the last exercise training session.

Exercise Procedure

The NMES and PMEF Groups were started on stimulation exercise sessions the week following (3-4 days) their MVC torque testing. The sessions (using involuntary contractions) were conducted three times per week for a total of four weeks. An exercise session consisted of ten, ten-second stimulation contractions, with each contraction separated by a 50-second rest period. Subjects in each

group had received a total of 120 induced involuntary contractions at the end of the four-week experimental period.

An overview of the experimental outline for each group is as follows:

NMES Group (Neuromuscular Electrical Stimulation)

Week 1

1) Randomly assigned to the NMES Group with subjects blind to group assignment.

2) Conducted practice session and tested the torque produced by MVC of the quadriceps femoris muscles.

Week 2 to 5

1) The Cybex II dynamometer was calibrated prior to all testing sessions.

2) Subjects were seated, with the leg of the dominant limb secured to the Cybex II dynamometer moment arm, and with the thigh and waist strapped down. The knee and hip were positioned in 60^0 of flexion.

3) Water soaked sponges and carbon rubber electrodes were attached to the subject's dominant thigh. One stimulating electrode was placed on the subject's skin over the femoral nerve at the femoral triangle in a vertical fashion. The other identical electrode was placed over the midportion of the vastus medialis muscle in a vertical fashion. Both electrodes were held firmly in place by velcro straps applied circumferentialy. Four layers of toweling were applied over the thigh and electrodes, on top

of which was applied the large magnetic stimulation coil (26 cm diameter). Two velcro straps were applied in a circumferential fashion to hold the stimulation coil in place.

4) With the NMES and magnetic stimulators concealed behind a curtain, NMES current amplitude was adjusted manually to maximal subject tolerance during the first contraction. The NMES stimulator was then set to automatic mode. Once a muscle contraction intensity of at least 30% MVC was achieved, a tape recording of the noise produced by the magnetic stimulator was manually activated. The recorded noise was activated concomitantly with the electrical stimualtion and administered during all subsequent contractions. To account for current accommodation, stimulus amplitude was manually increased to maximum subject tolerance after the first three seconds of each exercise contraction. Subjects were verbally notified 5 seconds before the onset of stimulation for each contraction.

5) The subject was not given any feedback (visual or auditory) about his or her performance during any exercise contraction. All subjects who tolerated electrically induced muscle contraction intensities of 30% of MVC or greater were told "good job" at the end of the exercise contraction. Subjects unable to tolerate an involuntary muscle contraction intensity of 30% MVC were eliminated from this study.

6) Stimulation characteristics were:

Pulse frequency - 50 bursts per second of a 2,500 HZ carrier wave.

Ramp time - two seconds.

On time - 10seconds.

Off time - 50 seconds.

Current - amplitude adjusted to subject's maximum tolerable level, measured in milliamperes.

7) One exercise session consisted of ten exercise contractions

8) Current amplitude and peak torque were recorded for all contractions (contraction 1 to 120).

9) At the end of the first and last exercise session, each subject completed a McGill Pain Questionnaire and a 10-cm visual analog scale. The McGill Pain Questionnaire was used to assess subject's pain level and the 10-cm visual analog scale was used to assess subject's perceived contraction intensity.

10) All subjects were asked not to alter their activity level during this four-week time period

Week 6

Both limbs were retested for torque produced by MVC of the knee extensor muscles.

PMEF group (combined electrical/magnetic stimulation)

Week 1

1) Randomly assigned to the PMEF Group, with subjects blind to group assignment.

2) Conducted practice session and tested for torque produced by MVC of the quadriceps femoris muscles.

Week 2 to 5

1) The Cybex II dynamometer was calibrated prior to all testing sessions.

2) Subjects were seated, with the leg of the dominant limb secured to the Cybex II dynamometer moment arm, with the thigh and waist secured by straps. The knee and hip were positioned in 60^0 of flexion.

3) Water soaked sponges and carbon rubber electrodes were attached to the subject's dominant thigh. One stimulating electrode was placed on the subject's skin over the femoral nerve at the femoral triangle in a vertical fashion. The other identical electrode was placed over the midportion of the vastus medialis muscle in a vertical fashion. Both electrodes were held firmly in place by velcro straps applied circumferentialy. Four layers of toweling were applied over the thigh and electrodes, on top of which was applied the large magnetic stimulation coil (26 cm diameter). Two velcro straps were applied in a circumferential fashion to hold the stimulation coil in place.

4) With the NMES and magnetic stimulators concealed behind a curtain, NMES current amplitude was adjusted manually to subject tolerance during the first contraction. When a muscle contraction of at least 30% MVC was obtained, the magnetic stimulator was manually activated at an

intensity setting of four. The NMES stimulator was then set on automatic mode. To account for current accommodation, the intensity of the magnetic stimulator was increased according to subject tolerance to its maximum setting of six. After achieving maximum intensity magnetic stimulation, NMES stimulus amplitude was manually increased to maximum subject tolerance after the first three seconds of each exercise contraction. Subjects were verbally notified 5 seconds before the onset of stimulation for each contraction.

5) The subject was not given any feedback (visual or auditory) about his or her performance during any exercise contraction. All subjects who tolerated involuntary muscle contraction intensities of at least 30% MVC or greater were told "good job" at the end of the exercise contraction. Subjects unable to tolerate a NMES induced involuntary muscle contraction intensity of at least 30% MVC were eliminated from this study.

6) Stimulation characteristics were:

Pulse frequency - 50 bursts per second of a 2,500 Hz carrier wave.

Ramp time - two seconds.

On time - ten seconds.

Off time - 50 seconds.

Current - amplitude adjusted to subject tolerance at the beginning of each contraction, measured in milliamperes.

7) One exercise session consisted of ten exercise contractions.

8) Current amplitude and training contraction intensity (expressed as a percentage of exercise contraction torque/MVC torque) were recorded for all contractions (contraction 1 to 120).

9) At the end of the first and last exercise session, each subject completed a McGill Pain Questionnaire and a 10-cm visual analog scale. The McGill Pain Questionnaire was used to assess subject's pain level and the 10-cm visual analog scale was used to assess subject's perceived contraction intensity.

10) All subjects were asked not to alter their activity level during this four-week time period.

Week 6

Both limbs retested for torque produced by MVC of the quadriceps femoris muscles.

Analysis of Data

A SYSTAT packaged computer program was used to perform all statistical analyses of the data. Analysis included computing the descriptive statistics (mean, standard deviation, and range) of subject demographic data as well as the following dependant variables: Pretest and posttest knee extensor muscle torque produced by MVC; pretest and posttest torque differences; perceived contraction intensity; pain

ratings; training contraction intensity; and current amplitude.

A 2 X 2 X 2 anaylysis of variance for repeated measures (Treated limb, Control limb, and Group) was used to analyze mean torque changes between the groups. Since no significant difference in pre-test torque was found, an analysis of covariance prodecure was not required. A 2 X 2 analysis of variance for repeated measures (Group and Time) was used to analyze the mean differences in perceived pain intensity, pain quality, and perceived contraction intensity between the groups. Because the difference in pre-treatment perceived contraction intensity showed a trend toward significance, these data were subsequently analyzed with an analysis of covariance with the pre-treatment perceived contraction intensity used as the covariate. A one way analysis of variance and intraclass correlation coeficient was used to determine the reliability of the 10-cm visual analog scale. The differences in mean training contraction intensity and mean electric current intensity between the two groups were analyzed with a one way analysis of variance. A probability level of .05 was used to determine significance in all statistical analyses.

CHAPTER 4

RESULTS AND DISCUSSION

Results

Torque

Descriptive statistics for the groups pretest, posttest, and change torque scores (expressed as a percentage of the pretest torque score) are presented in Table 2. A three way analysis of variance for repeated measures, summarized in Table 3, was used to analyze these data. Although the PMEF group experienced a greater increase in torque from pretest to posttest, the group by treated interaction showed no statistically significant differences in torque gain between the groups. The treated limb of both groups demonstrated a significant increase in posttest torque scores. The group by control interaction shows that although statistically significant torque gains in the control limb were made by both groups, there was no significant difference between the groups. The analysis of control limb torque gain also showed a significant increase in posttest torque scores for both groups. The treated by control limb interaction shows that the treated limb of both groups demonstrated significantlly greater torque gains at posttest than the control limb. This increased torque indicates that the stimulation elicited a training effect. The three-way

Table 2

Descriptive Statistics for Group Pretest, Posttest, and Percentage Change Quadriceps Femoris Muscle Torque Scores (Nm)

Group	Time and Condition					
	Pretest		Posttest		% Change	
Statistic	Treat	Control	Treat	Control	Treat	Control
NMES						
-						
X	203.0	194.0	229.0	205.0	13.0	6.0
SL	57.1	63.6	66.7	66.1	.1	.1
Min	105.8	109.8	119.3	111.2	-12.0	-6.0
Max	313.2	317.3	340.7	341.7	44.0	44.0
PMEF						
-						
X	191.0	189.0	223.2	200.0	17.0	6.0
SD	60.9	67.2	76.0	63.3	.2	.1
Min	86.8	78.6	120.7	103.1	0.0	-7.0
Max	329.5	343.1	358.0	328.2	52.0	31.0

Table 3

Summary of the Three-way Analysis of Variance for Knee Torque

Source	df	SS	MS	F
Group	1	1810.73	1810.73	.11[a]
Error	38	611348.57	16088.12	
Treated	1	8989.05	8989.05	24.97*
Error	38	13679.58	359.989	
Group x Treated	1	130.29	130.29	.36[a]
Error	38	13679.58	359.99	
Control	1	14463.05	14463.05	39.75*
Error	38	13826.07	363.84	
Group x Control	1	75.93	75.93	.21[a]
Error	38	13826.07	363.84	
Treated x Control	1	3250.56	3250.56	16.24*
Error	38	7608.43	200.22	
Group x Treated x Control	1	131.99	131.99	.66[a]
Error	38	7608.43	200.22	

[a]NS.
*P < .05

interaction of group by treated limb by control limb was not statistically significant. There was no significant difference in pretest and posttest torque scores between groups for either the treated or the control limb. Therefore, there was no significant difference in torque gains between the groups at posttest for either the treated or control limb.

The strength gains of the treated limbs for the NMES and PMEF groups were 13% and 17%, respectively. The

strength of the control limb increased 6% in both groups. These results are illustrated in Figure 1. along with the average training contraction intensity (%MVC) of both groups.

Pain

The intensity and quality of pain experienced by subjects was measured using the McGill Pain Questionnaire (short form) previously described in Chapter 3. Subjects filled out the forms after their initial and final exercise sessions.

The descriptive statistics for initial, final, and change scores for the 10-cm visual analog scale (10-cm VAS) are presented in Table 4. The data were analyzed using a two way analysis of variance for repeated measures and the results are summarized in Table 5. While the PMEF group had a somewhat higher initial pain intensity score, there was no statistically significant difference between the groups. Even though both groups tolerated progressively higher current amplitudes in every exercise session, there was no significant increase in pain reports over time for either group. Figure 2 illustrates the mean current amplitudes of each group by exercise session. The interaction of group by time was not statistically significant.

To determine the reliability of the 10-cm VAS when measuring pain caused by electrical stimulation, eight randomly chosen subjects scored a 10-cm VAS after every exercise session.

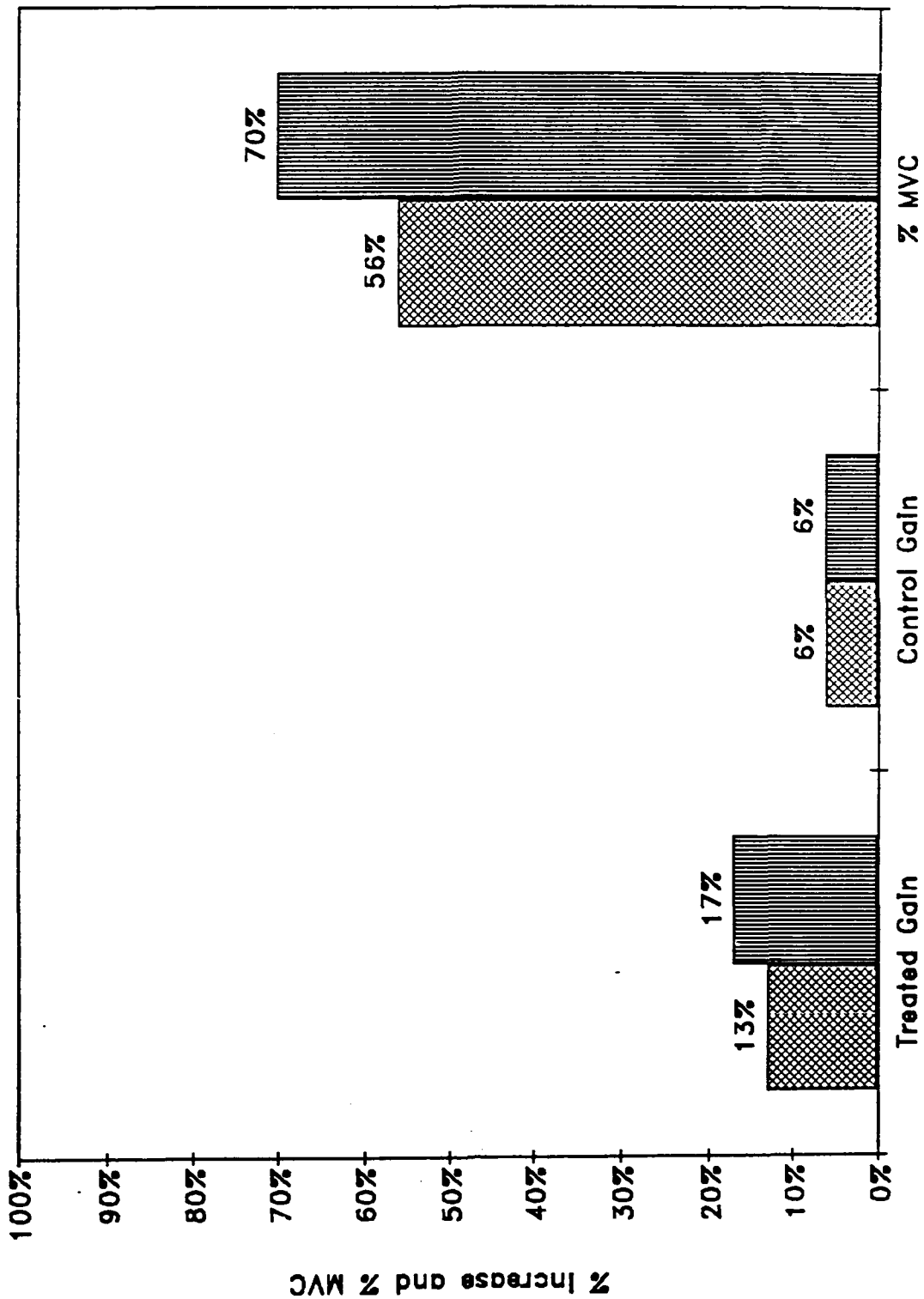

Fig. 1
Strength Gains and Training % MVC

Table 4

Pain Intensity: Descriptive Statistics for Initial, Final and Change Scores as Measured by the 10-cm Visual Analog Scale

Time	Group	
	NMES	PMEF
Initial		
$\bar{X}$	2.8	3.3
SD	1.9	1.9
Min	0.5	0.0
Max	7.2	7.2
Final		
$\bar{X}$	3.4	3.7
SD	2.5	2.1
Min	0.2	0.0
Max	8.7	7.0
Change		
$\bar{X}$	0.7	0.4
SD	2.2	1.9
Min	-5.6	-2.2
Max	4.9	3.7

Table 5

Summary of the Two-Way Analysis of Variance for 10-cm Visual Analog Scale Pain Scale Ratings

Source	df	SS	MS	F
Group	1	2.99	2.99	.45[a]
Error	38	250.37	6.59	
Time	1	5.97	5.97	2.69[a]
Error	38	84.28	2.22	
Group x Time	1	.22	.22	.10[a]
Error	38	84.28	2.22	

[a]NS

Table 6 summarizes the one way analysis of variance and intraclass correlation coefficient (ICC) used to analyze the data. The ICC of .95 shows the 10-cm scale to be a very reliable instrument when measuring pain caused by electrical stimulation.

The present pain index (PPI), an interval level scale, was also used to measure pain intensity. The descriptive statistics for initial, final, and change scores are presented in Table 7. All scores for both groups are nearly identical. A two way analysis of variance for repeated measures was used to analyze the data and the results are presented in Table 8. No significant differences were noted for either group, or time, or the group by time interaction. Both the 10-cm VAS and PPI show that pain intensity levels were the same for both groups and that neither group

Table 6

Summary of the One Way Analysis of Variance and Intraclass Correlation Coefficient for Repeated 10-cm Visual Analog Pain Scale Ratings

Source	df	SS	MS	F
Treatment	11	24.57	2.23	0.12[a]
Subjects	7	342.64	48.95	2.69[a]
Interaction	77	1359.95	17.66	0.97[a]
Error	95	1727.16	18.18	

Summary of Intraclass Correlation

$$R = \frac{MS\ treatment - MS\ subjects}{MS\ subjects} = .95$$

[a]NS

Table 7

Pain Intensity: Descriptive Statistics for Initial, Final and Change Scores as Measured by the Present Pain Index Scale

Time	Group	
	NMES	PMEF
Initial		
$\bar{X}$	1.5	1.4
SD	0.8	0.9
Min	0.0	0.0
Max	3.0	3.0
Final		
$\bar{X}$	1.7	1.6
SD	1.0	0.7
Min	0.0	0.0
Max	4.0	3.0
Change		
$\bar{X}$	0.2	0.2
SD	0.9	0.9
Min	-2.0	-2.0
Max	2.0	2.0

Table 8

Summary of the Two Way Analysis of Variance for the Present Pain Index Pain Scale Ratings

Source	df	SS	MS	F
Group	1	.16	.16	.15[a]
Error	38	40.04	1.05	
Time	1	.78	.78	1.84[a]
Error	38	16.17	.43	
Group x Time	1	.03	.03	.07[a]
Error	38	16.17	.43	

[a]NS

experienced an increase in pain report over the four-week training period.

Table 9 presents the descriptive statistics for each group for the number of initial and final sensory pain indicators chosen and the difference between them. The results of the two way analysis of variance for repeated measures used to analyze the data are presented in Table 10. There was no significant differences between the groups, or over time, or for the group by time interaction.

Table 11 presents the descriptive statistics for each group for the number of initial and final affective pain indicators chosen and the difference between them. The results of the two way analysis of variance for repeated measures used to analyze the data are presented in Table 12. There were no significant differences between the groups,

Table 9

Pain Quality; Descriptive Statistics of Initial, Final, and Change Scores for the Number of Sensory Pain Descriptors Chosen

Time	Group	
	NMES	PMEF
Initial		
$\bar{X}$	3.5	4.0
SD	2.6	3.6
Min	0.0	0.0
Max	12.0	11.0
Final		
$\bar{X}$	4.6	4.1
SD	3.5	3.4
Min	1.0	0.0
Max	13.0	12.0
Change		
$\bar{X}$	1.1	0.1
SD	3.2	3.2
Min	-7.0	-6.0
Max	8.0	6.0

Table 10

Summary of the Two Way Analysis of Variance for the Number of Sensory Pain Descriptors Chosen

Source	df	SS	MS	F
Group	1	.02	.02	.00[a]
Error	38	631.17	16.61	
Time	1	5.93	5.93	1.14[a]
Error	38	197.76	5.20	
Group x Time	1	7.13	7.13	1.37[a]
Error	38	197.76	5.20	

[a]NS

Table 11

Pain Quality: Descriptive Statistics of Initial, Final, and Change Scores for the Number of Affective Pain Descriptors Chosen

Time	Group	
	NMES	PMEF
Initial		
$\bar{X}$	0.9	1.3
SD	1.2	1.8
Min	0.0	0.0
Max	5.0	7.0
Final		
$\bar{X}$	1.1	1.2
SD	1.5	1.3
Min	0.0	0.0
Max	6.0	4.0
Change		
$\bar{X}$	0.2	-0.1
SD	1.0	1.1
Min	-1.0	-3 0
Max	3.0	2.0

Table 12

Summary of the Two Way Analysis of Variance for the Number of Affective Pain Descriptors Chosen

Source	df	SS	MS	F
Group	1	1.12	1.12	.29[a]
Error	38	145.37	3.83	
Time	1	.01	.01	.02[a]
Error	38	20.88	.55	
Group x Time	1	.61	.61	1.11[a]
Error	38	20.88	.55	

[a]NS

or over time, or for the group by time interaction.

Table 13 presents the descriptive statistics for each group for the number of initial and final total pain indicators chosen and the difference between them. No large differences between the groups exists for the total number of pain indicators chosen. This was expected as the comparisons of both sensory and affective pain descriptors showed very little difference between the groups. The results of the two way analysis of variance for repeated measures used to analyze the data are presented in Table 14. Once again, there is no difference between the groups, or over time, or for the group by time interaction.

There was no difference in the number of sensory, affective, or total number of pain quality indicators chosen. Therefore, the quality of pain experienced by

Table 13

Pain Quality: Descriptive Statistics of Initial, Final and Change Scores for the Total Number of Pain Descriptors Chosen

Time	Group	
	NMES	PMEF
Initial		
$\bar{X}$	4.4	5.4
SD	3.5	4.8
Min	1.0	0.0
Max	17.0	17.0
Final		
$\bar{X}$	5.7	5.2
SD	4.2	4.4
Min	1.0	0.0
Max	15.0	14.0
Change		
$\bar{X}$	1.3	-0.2
SD	3.3	3.9
Max	-6.0	-9.0
Min	8.0	7.0

Table 14

Summary of the Two Way Analysis of Variance for the Total Number of Pain Descriptors Chosen

Source	df	SS	MS	F
Group	1	1.44	1.44	.05[a]
Error	38	1119.12	29.45	
Time	1	6.29	6.29	.97[a]
Error	38	245.91	6.47	
Group x Time	1	11.89	11.89	1.84[a]
Error	38	245.91	6.47	

[a]NS

subjects in the NMES and PMEF groups was not different.

Perceived Contraction Intensity

Perceived contraction intensity, a sensation different from pain, was also measured with a 10-cm VAS. The descriptive statistics for the initial, final, and change scores of the perceived contraction intensity ratings are presented in Table 15. The PMEF group rated the contractions of their initial and final exercise sessions as being more intense than the contractions experienced by the NMES group. The change score of the PMEF group is also larger, indicating they experienced a greater increase in contraction intensity over time than the NMES group. A two way analysis of variance for repeated measures was used to analyze the data and the results are summarized in Table 16.

Table 15

Descriptive Statistics of Initial, Final and Change Scores for Perceived Contraction Intensity Ratings as Measured by the 10-cm Visual Analog Scale

Time	Group	
	NMES	PMEF
Initial		
$\bar{X}$	6.2	6.7
SD	2.2	2.0
Min	2.1	2.9
Max	9.9	9.1
Final		
$\bar{X}$	6.5	7.9
SD	2.4	1.4
Min	1.1	3.4
Max	9.7	9.8
Change		
$\bar{X}$	0.3	1.2
SD	2.2	1.4
Min	-6.7	-1.5
Max	3.6	3.7

Table 16

Summary of the Two Way Analysis of Variance for 10-cm Visual Analog Scale Perceived Contraction Intensity Ratings

Source	df	SS	MS	F
Group	1	18.85	18.85	2.88[a]
Error	38	249.07	6.55	
Time	1	11.64	11.64	6.69*
Error	38	66.17	1.74	
Group x Time	1	3.62	3.62	2.08[a]
Error	38	66.17	1.74	

[a]NS
*P < .05

A statistically significant difference existed between the groups over time. However, the group over time interaction was not statistically significant. This finding suggests that while contraction intensity did significantlly increase over time, there was no difference in this increase between the groups. The results of the group analysis, though not significant, did show a trend toward significance. To examine this trend more carefully, an analysis of covariance using the initial contraction intensity scores as the covariate was applied to the data to eliminate any confounding effect on the group comparison caused by initial score differences. Table 17 summarizes the results of the analysis of covariance. This analysis revealed that the PMEF Group did perceive a statistically significant

Table 17

Summary of the Analysis of Covariance for 10-cm Visual Analog Scale Perceived Contraction Intensity Ratings Using the Pretest Perceived Contraction Intensity Ratings as the Covariate

Source	df	SS	MS	F
Group	1	11.89	11.89	4.54*
Error	37	97.01	2.62	

*P < .05

stronger contraction intensity than the NMES group.

Training Contraction Intensity and Current Amplitude

The torque produced during stimulation was recored for all subjects and for every exercise contraction. Training contraction intensity, expressed as a percentage of the subjects pretest MVC, was then calculated and recorded. The maximum current amplitude (mA) tolerated by subjects during each induced contraction was recorded also. All PMEF group subjects tolerated the maximum output of the magnetic stimulator by the second exercise session. These data were collected to determine if the groups differed in their training contraction intensity and level of maximum current amplitude.

The descriptive statistics for NMES and PMEF subjects training contraction intensity and maximum current amplitude are presented in Tables 18 and 19, respectively. The

Table 18

Descriptive Statistics for Subject Training Contraction Intensity and Current Amplitude

NMES Group	Variable					
	Current Amplitude (mA)			Training Intensity (%MVC)		
Subject	$\bar{X}$	Min	Max	$\bar{X}$	Min	Max
1	37	13	66	63	16	87
2	51	10	70	41	0	93
3	24	0	32	55	5	95
4	41	10	72	72	15	101
5	36	6	51	38	7	60
6	40	12	59	68	6	92
7	21	10	27	15	0	31
8	34	12	47	33	4	50
9	43	2	63	58	12	78
10	36	2	46	54	0	84
11	22	10	36	53	10	82
12	47	5	100	61	15	96
13	34	45	64	49	3	83
14	67	17	100	65	5	116
15	22	12	54	62	6	126
16	33	12	54	62	6	107
17	26	14	34	51	10	105
18	42	16	100	57	11	85
19	36	12	59	77	10	115
20	58	18	100	79	20	112
21	35	20	50	52	7	92

Table 19

Descriptive Statistics for Subject Training Contraction Intensity and Current Amplitude

PMEF	Variable					
	Current Amplitude (mA)			Training Intensity (%MVC)		
Subject	$\bar{X}$	Min	Max	$\bar{X}$	Min	Max
1	18	11	25	84	25	120
2	43	14	80	98	11	124
3	40	10	64	61	6	84
4	22	2	39	54	9	84
5	19	12	33	55	3	81
6	37	13	71	59	0	105
7	21	0	28	74	15	104
8	54	12	100	78	10	108
9	53	10	83	59	3	78
10	39	10	60	86	6	122
11	21	8	34	81	6	107
12	73	20	100	101	8	145
13	48	22	78	57	17	85
14	71	18	100	43	7	84
15	52	18	70	89	14	111
16	45	20	74	78	10	102
17	25	12	38	56	11	94
18	48	18	100	77	18	106
19	28	16	41	40	10	83

descriptive statistics for both the groups are presented in Table 20. The results of the one way analysis of variance used to analyze training contraction intensity and maximum current amplitude are presented in Tables 21 and 22, respectively. The PMEF group's training contraction intensity is 14% greater than the NMES group's and is statistically significant. The difference in maximum current amplitude is negligable and is not statistically

Table 20

Descriptive Statistics for Group Training Contraction Intensity and Electrical Current Amplitude

	Training Contraction Intensity (% MVC)				Electrical Current Amplitude (mA)			
Group	$\bar{X}$	SD	Min	Max	$\bar{X}$	SD	Min	Max
NMES	56	14.9	15	79	38	11.7	21	67
PMEF	70	17.8	40	101	40	16.8	18	73

Table 21

Summary of the One Way Analysis of Variance for Group Mean Training Contraction Intensity

Source	df	SS	MS	F
Group	1	2104.14	2104.14	7.89*
Error	38	10129.24	266.56	

*P < .05

Table 22

Summary of the One Way Analysis of Variance for Group Mean Maximum Current Amplitude

Source	df	SS	MS	F
Group	1	54.29	54.29	.26[a]
Error	38	7843.38	206.41	

[a]NS

significant.

It can be seen from these data that the range of training contraction intensity and maximum current amplitude varies greatly between subjects in both groups. There is also a large variation in the maximum current amplitude level and resultant training contraction intensity between subjects in both groups.

Several subjects reported muscle soreness in the treated limb after the first exercise session. This soreness resolved after the second or third exercise session. One subject from each group developed patello-femoral pain. In addition, one subject from each group incurred a mild strain of the quadriceps femoris muscle. The strains occurred in the seventh and twelfth exercise session during contractions in excess of 100% of the subjects MVC. One subject from each group failed to achieve an induced contraction of at least 30% of their MVC and were eliminated from the study.

Sixteen of the twenty-one subjects in the NMES group trained at a contraction intensity greater than 50% MVC. None of the subjects in the NMES group had a mean training contraction intensity greater than 100% MVC. There were four subjects who acheived the maximum current output of the electrical stimulator.

Seventeen of the 19 subjects in the PMEF group trained at a contraction intensity greater than 50% MVC. One subject had a mean training contraction intensity greater

than 100% MVC (subject 12). All PMEF subjects achieved the maximum current ouput of the magnetic stimulator by the second exercise session. There were also four subjects in each group who achieved the maximum current output of the electrical stimulator. Figure 2 graphically contrasts the mean training contraction intensities and maximum current amplitudes of both groups by exercise session. Figure 3 graphically contrasts the mean training contraction intensities and maximum current amplitudes of both groups by week.

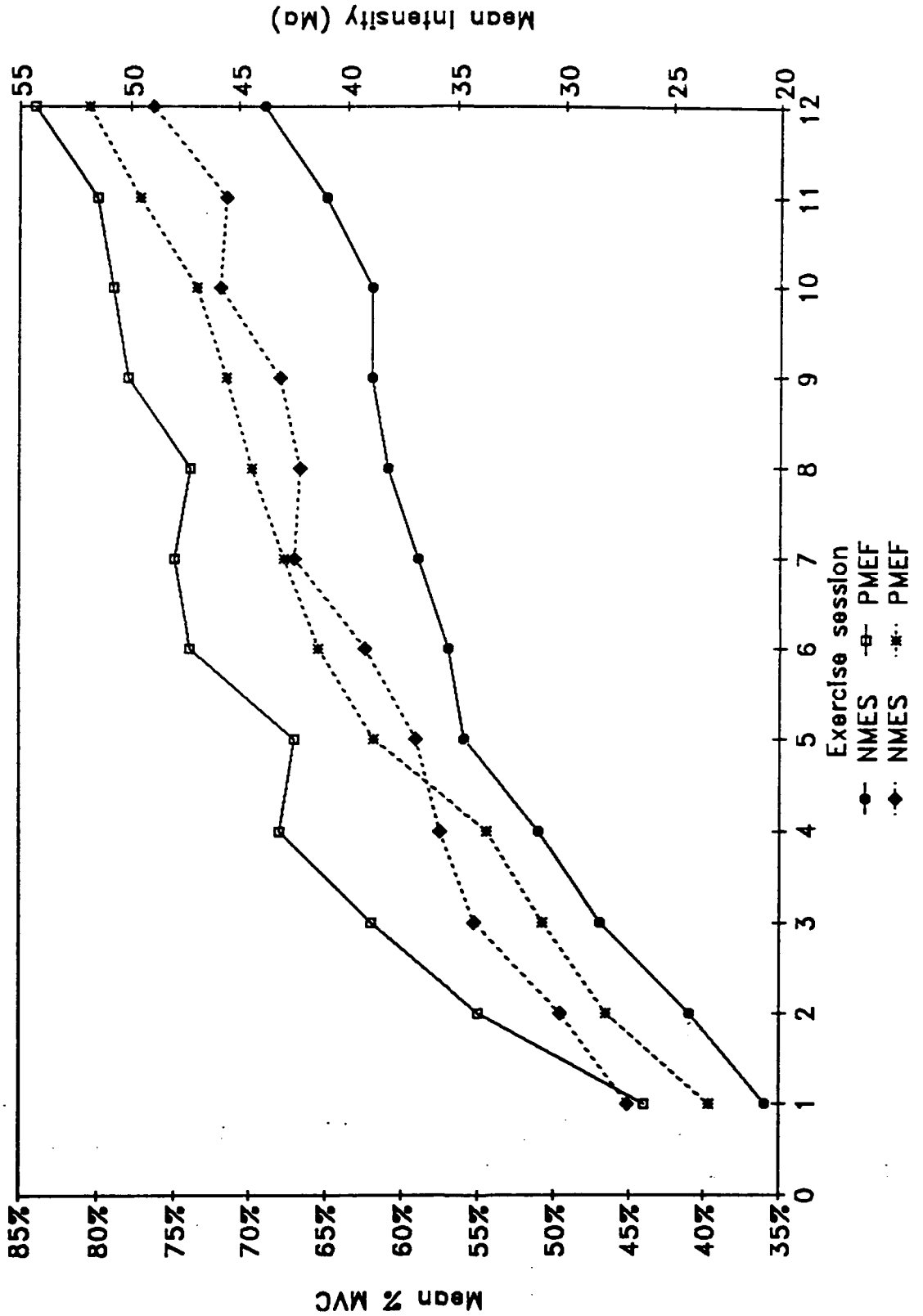

Fig 2.
% MVC and mA by Exercise Session

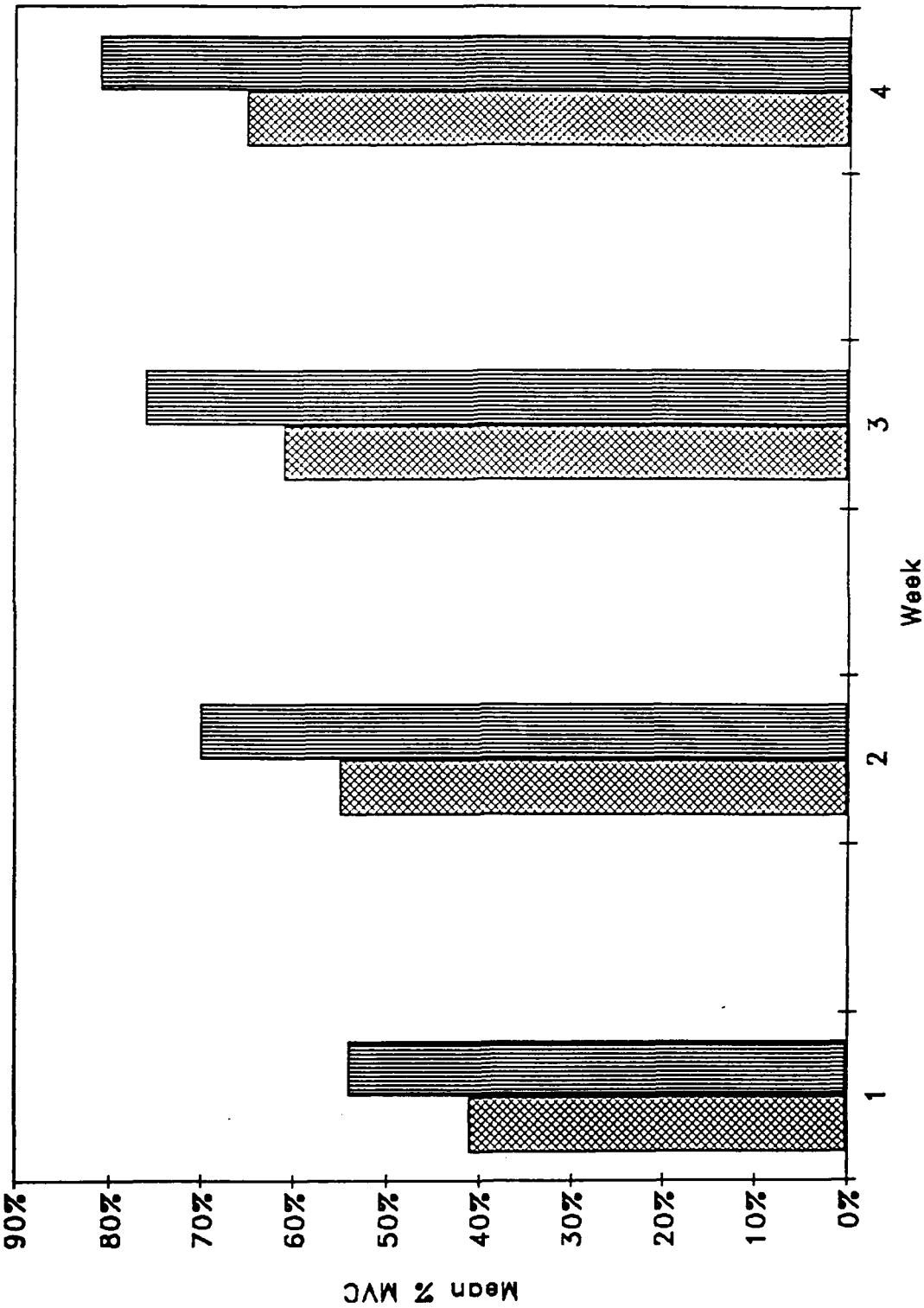

Fig. 3
% MVC by Week

Discussion

Torque

The treated limbs of the NMES and the PMEF Groups demonstrated a 14% and 17% strength increase, respectively, after the four-week training period. The occurrance of an increase in strength following a regimen of electrically induced contractions is consistent with the previous findings of other investigators.[6-15] Other studies using electrically induced contractions to train subjects report strength gains ranging from 18%[11] to 44%.[9] The reason for the somewhat lower strength gains of the groups in this study is unclear. One possible explanation is that the initial strength level of subjects in this study was proportionally higher than the subjects used in previous investigations.

Two measures were taken to ensure that strength increases were not attributable to factors other than the mode of stimulation applied to the limbs. First, all subjects were blind to group assignment. If PMEF subjects knew they were receiving two forms of stimulation instead of one, it might have influenced their test results. Second, a tape recording of the noise made by the magnetic stimulator was played during every exercise contraction for NMES subjects. The technical characteristics of the magnetic stimulator cause it to produce a loud noise during activation. This would have subjected PMEF subjects to

additional external stimuli not received by subjects in the NMES group.

Both verbal suggestion and loud noise have been shown to increase peak torque between consecutive tests of a single testing session.[86] Theoretically, this sudden increase in strength unrelated to training may result from disinhibitory or excitatory influences on the central nervous system. The influence of the noise produced by the magnetic stimulator on torque was not assessed in this study. If an effect did occur, its influence on group outcomes should have been equal as both groups were subjected to the same stimuli.

The strength gain of the PMEF Group's treated limb was not significantly different than the gain of the NMES Group. This result was in spite of the fact that the PMEF group trained at a significantly higher training contraction intensity (70%) than did the NMES group (56%). This discrepancy between training intensity and resultant torque gain was also observed for certain subjects in both groups. One subject in the PMEF Group who trained at a relatively high intensity (98% MVC) demonstrated very little strength gain (4% increase). Another subject in the NMES Group demonstrated a significant gain (30% increase) training at a relatively low intensity (55% MVC).

There are reports in the literature of trials inducing electrical contractions in which groups trained with intensity differences ranging from 45% MVC[11] to 50% MVC.[10]

The strength gains of the training groups in these studies were significantly greater than those of the control, but not significantly different from each other. Both studies reported that the hamstrings might have co-contracted during stimulation which would have caused a deflated training intensity score to be recorded. Voluntary co-contraction of the hamstrings would be unlikely however, with the exception of extreme pain, due to the effect of reciprocal inhibition.[87]

Another possible explanation is that the electrical current amplitude was great enough to overflow and stimulate the motor nerve of the hamstrings, thereby causing an induced contracton. Soo et al did not observe a strengthening effect of the hamstrings in subjects who demonstrated strength gains from electrically induced contractions.[6]

A discrepancy between training intensity and strength gains has also been documented for subjects trained with voluntary isometric contractions. Cotten observed groups that trained with remarkably different intensities without producing significantly different strength gains.[88]

Atha's review of the literature dealing with isometric exercise show that two predominate views exist on how strength gains occur from isometric training.[89] The first is that the strengthening stimulus is a threshold function. Hettinger and Muller established this threshold to be about 30% MVC; after which, they stated, any increases in tension

induced only minimal strength gains.[90] Cotten's work supports this concept. He found that strength gains induced when training at intensities of 50%, 75%, and 100% MVC were similar, but no strength gain occurred for subjects who trained at 25% MVC.[88]

The second view is that strength gains are largely associated with the intensity or magnitude of the training load. Coleman[91] as well as Walters, Steward, and LeClaire[92] observed greater strength gains in groups and individual subjects who trained at a higher percentage of their MVC. Atha states that after the values obtained by Cotten were normalized with respect to initial strength levels, a "rough" correlation did exist between the intensity of the load and resultant strength increases.[89]

Selkowitz reported a Pearson-product moment correlation of .61 between training intensity and strength gain.[9] The correlation between individual subject's training contraction intensity and strength gain was not formally assessed in this study. While training intensity and strength gain appear to be associated, the results of this study suggest that other factors are also important in strength development.

Several factors influence strength gains induced by training. These may include contraction intensity, duration, frequency, and length of the training program. The intensity of the training load is often thought to be the primary factor governing strength gain (peak torque).

While important, Atha's review led him to conclude that intensity has a ramp-function effect on isometric strength gains that is not fully understood. He cites work demonstrating that other factors, such as initial force development, can also have a profound effect on isometric strength gains.[89] The precise role training intensity plays in the development of isometric strength is still open to question.

It is possible that the difference in training contraction intensity between the groups in the present study may have caused significantly different strength gains if the length of training was increased to six or eight weeks. It has been demonstrated that the strength gains incurred in the first three to four weeks of training occur rapidly and are attributed primarily to neural factors; subsequent gains occur more slowly and are attributable to muscle hypertrophy.[93] Considerable hypertrophy was noted in two PMEF subjects who demonstrated strength increases of 38% and 40%. Notable hypertrophy was not observed in any NMES subjects. It is not clear whether this was the result of the training stimulus or variations in individual subjects' response. A longer training period might possibly clarify this question.

Other investigations have assessed the effect electrically induced contractions have on time to peak torque and power.[7,15] The effect PMEF training would have

on these strength variables is not known and requires further investigation.

The control limb of both groups demonstrated a 6% increase in strength that was significant. Examination of the raw data shows that gains of the control limb were variable between subjects in both groups. Approximately 70 percent of the subjects in each group had a strength increase of the control limb. The magnitude of gains were also highly variable, ranging from 1% to 44% of pretest values and in some cases exceeding the percentage gain of the treated limb.

The phenomenon of a strength increase in the untreated limb is often called a "cross-education" effect. This cross-education effect has been demonstrated in other studies involving voluntary[94-96] as well as electrically induced contractions.[11,96] and ranges from 10% to 30%. Enoka stated in his review that the strength increase of the trained limb is always greater than that of the control limb.[97] In this investigation, the strength increase for the trained limb of both groups was greater than that of the control limb. This was not always the case for individual subjects. Eight subjects demonstrated gains in the control limb that were 16% to 22% greater than those of the treated limb. With the exception of five subjects whose control limb was stronger at pretest, the posttest torque of the control limb never exceeded the posttest torque value of the treated limb.

Hellebrandt et al reported that the magnitude of gain induced in the contralateral limb was directly related to the intensity of exercise of the trained limb.[94] The results of this study do not support her conclusion. The gains of the control limb were identical for both groups even though they trained at significantly different contraction intensities.

Likely explanations for the strength increase demonstrated in the control limb include: 1) a learning effect occurred due to the pretesting session 2) a training effect occurred due to the muscular contraction of the control limb when providing support during exercise 3) a centrally located (possibly the interneuronal connections between limbs) adaptation occurred as a result of overflow from the stimulus applied to the trained limb.[97]

It is unlikely that a learning effect resulting from repeated testing could account solely for the strength increase seen in the control limb. For some subjects, the gains were substantial. The familiarization session, which included electrical stimulation contractions, should have diminished the influence of a learning effect. Training of the control limb due to stabilizing muscular contraction during training of the contralateral muscle does not have strong support either. Houston et al reported no change in muscle fiber area or enzyme activities in limbs that exhibited a cross-education strength increase.[95] The most probable explanation is that of a centrally mediated neural

adaptation. This would be consistent with the fact that early strength gains of the treated limb primarily result from neural mediated factors.

Training Intensity and Current Amplitude

The training contraction intensity, expressed as a percentage of the pretest torque score, and maximum electrical current amplitude of every exercise contraction was recorded for all subjects. All subjects in the PMEF Group were receiving the maximum output of the magnetic stimulator by the second exercise session. Therefore, a comparison of the the maximum tolerated electrical current amplitude was made between the groups. Though training contraction intensity and maximum electrical current amplitude were not the main variables assessed in this study, it was believed they might provide insight into any differences that exist between NMES and PMEF stimulation.

The significant difference in training contraction intensity between the groups and implications for the resulting insignificant strength gains has been previously discussed. Since the electrical current amplitude received by the NMES and PMEF Groups was essentially the same, the difference in the PMEF Group training contraction intensity must be attributed to the magnetic stimulation. The difference in contraction intensity may simply be a result of the PMEF Group receiving an additional source of stimulation. Another explanation is that the magnetic

stimulation augmented the electrical current received by the PMEF Group. Kellogg reported a mean augmentation effect for torque occurs when magnetic stimulation was combined with maximally tolerated electrical stimulation. The resulting difference in torque produced by the PMEF stimulation and maximum electrical stimulation alone was 14%.[17] This is precisely the difference between the two stimulation groups in this study.

A high degree of variability existed between subjects in both groups for the torque produced per amount of current delivered (see Tables 18 and 19). There were seven subjects in the NMES Group and eleven subjects in the PMEF Group who attained training contraction intensities greater than 100% MVC. These training intensities may be an overestimation of the percentage of MVC actually produced. The contraction intensities reported in this study were derived using the pretest peak torque score. The true peak torque value of the limbs was probably increasing throughout the course of the study. The ability of electrical stimulation to induce contractions greater than MVC has been documented by others.[9,41]

The variability in torque produced relative to the amount of current delivered has also come to the attention of other investigators.[9,21,52] Investigators of a recent study have tried to quantify and explain the amount of torque output in response to electrical current received. They termed this relationship "stimulation efficiency".[98]

Stimulation efficiency is defined as the extension torque output relative to the stimulation current received (in Newton-meters per milliampere). Stimulation efficiency is said to represent the intrinsic tissue property relating current input to knee torque output. The multiple regression analysis of their data revealed that current, voltage, and impedance combined accounted for only 12% of the variance, while stimulation efficiency accounted for 76% of the variance. They concluded that torque production by subjects in response to electrical stimulation is based primarily on inherent characteristics of the tissue stimulated.[98] The amount of subcutaneous fat, nerve fiber composition, or superficial branching patterns of the motor nerve are all possible explanations of why subjects differ in their response to electrical stimulation.

Further research is required to determine exactly what factors cause some subjects to respond more efficiently (extension torque per milliamperes) to electrical stimulation than others. Work done to correlate stimulation effeciency with body composition and muscle fiber type might elucidate our understanding of subject response to electrical stimulation.

The mean maximum current amplitude tolerated by both groups was nearly identical and not significantly different. A high degree of variability also existed between subjects in both groups for the maximum current amplitude tolerated (see Tables 18 and 19). Four subjects in each group

tolerated the maximal output of the electrical stimulator. All subjects tolerated progressive increases in current amplitude over time to varying degrees, indicating that they accommodated to the current. Other investigators have also noted that subjects become less sensitive, or accommodate, to electrical stimulation over time.[8,11,15,21,52]

Sensory Perception Changes

Huskisson has demonstrated that the 10-cm VAS is a valid and reliable tool for measuring pain.[85] Clinically, many subjects describe pain caused by electrical stimulation as being different from pain they experience because of other nociceptive stimuli. Transcutaneous electrical nerve stimulation can cause altered sensory perception and is often used clinically to diminish pain. In order to assess the reliability of the 10-cm VAS when measuring electrical stimulation pain, eight subjects scored the 10-cm VAS after every exercise session. A intraclass correlation coefficient of .95 shows the 10-cm VAS to be reliable when measuring pain caused by electrical stimulation over reapeted applications.

The scores from the 10-cm VAS and PPI both showed that pain intensity was mild to moderate for both groups and did not significantly increase over time for either group. This was in spite of the fact that both groups progressively increased the amount of electrical current received. The difference in current amplitude between the initial and final exercise session for both groups was approximately 23

milliamperes. The process of accommodation described previously probably accounts for why a much larger current amplitude was tolerated without a concomitant increase in pain.

Kellogg found that subjects receiving NMES had higher pain ratings than subjects receiving magnetic stimulation only.[21] He mentioned that this was possibly caused by the limited output capabilities of the magnetic stimulator, which prevented a progressive increase in current amplitude as experienced by the NMES Group. Kellogg also found that pain increased over time for subjects receiving NMES. A pain increase for NMES Group subjects was not found in this study.[21]

Currier et al found that patients recovering from ACL ligament reconstruction rated PMEF stimulation as being 50% less painful than NMES.[22] The use of a cross-over design and post-surgical subjects by Currier however, prevent a valid comparison of the results from his study and this one. The findings of this study do not support one type of stimulation as being more comfortable than the other.

Because the PMEF Group demonstrated a higher training intensity, there might possibly be a pain contribution from the muscular contraction in addition to the cutaneous discomfort caused by NMES. Selkowitz reported that subjects trained with electrical stimulation in his study rarely complained of pain from the electrical current but did report discomfort from the induced contraction.[9] Boutelle

also reported that many subjects in his study experienced a cramping type pain that was said to be correlated with the intensity of the induced contraction.[8] Kramer has mentioned that a variety of factors, including electrode size and positioning, skin moisture content, and psychological profile can alter the degree to which the electrical stimulus and resultant contraction are perceived as uncomfortable.[42]

Controlling the contraction intensities of subjects receiving NMES and PMEF would allow a more valid comparison of the pain associated with each type of stimulation. Because of the unequal training contraction intensities of the two groups, the question of whether or not PMEF stimulation is more comfortable than NMES remains unresolved.

There was no difference in the number of sensory or affective pain descriptors reported by either group. Therefore, the quality of pain experienced by the groups was the same and remained unchanged over time.

Currier and Mann have shown that pain caused by electrical stimulation is primarily sensory and transient in nature, as opposed to affective.[16] No consistent pattern was seen in this study which indicated that individual sensory or affective descriptors were most frequently chosen. Because of this inconsistency, no attempt was made to categorize or analyze these data.

The perceived contraction intensity ratings of the PMEF Group at posttesting were significantly higher than those reported by the NMES Group. The fact that the PMEF Group actually trained at a significantly higher training intensity shows the 10-cm VAS to be a valid tool for measuring perceived contraction intensity. Caution should be exercised when using this scale to detect small differences between groups. The PMEF group demonstrated a training intensity 14% greater than that of the NMES group. which is a rather large difference.

Adverse Effects

In addition to mild pain from stimulation, most subjects experienced muscle soreness that resolved after the first week of training. This delayed onset of muscle soreness has occurred in numerous other studies employing electrically induced contractions[6,8, 9,11,15,21,52] and is observed when training with volitional contractions, also.

Another observation with regard to muscle soreness was noted in several subjects from both groups. Many subjects who experienced acute muscle soreness complained of intense pain when stimulated with relatively low current amplitudes compared to the first several contractions of their initial exercise session. The complaint was primarily associated with the induced muscle contraction, which was also less intense than the initial contractions of the previous session, and not the cutaneous pain produced by electrical stimulation. As the exercise session progressed, greater

current amplitudes and training contraction intensities were tolerated while the pain from the muscle contraction concomitantly diminished. By the end of the exercise session, many subjects experienced no muscular pain and achieved maximum current amplitudes and training contraction intensities comparable with those of the initial exercise session. The mechanism responsible for this is unclear, but it would lend support to the metabolic theory of muscle soreness.[99] Increased blood flow in the tissue resulting from NMES induced contractions[100] would allow metabolic waste products to be removed and supply additional oxygen and nutrients to the area.

One subject in the NMES Group experienced a 12% and 5% torque decrease in the treated and control limb, respectively, after completing the training regimen. No one in the PMEF Group experienced a torque decrease. The NMES subject who demonstrated a decrease reported that her activities had not changed over the four-week training period. There are other reports in which a few individual subjects show a decrease in torque after training with electrically induced[21] and voluntary contractions.[12] It is unclear how often a strength decrement occurs with NMES training because not all investigators report their data for individual subjects. The extent to which electrical stimulation was responsible for the decrease in strength experienced by this subject is unclear. It is not known whether electrical stimulation produces a detrimental effect

on strength for predisposed individuals. Since torque decrement appears to occur in only a few individuals, large sample trials are needed to answer this question.

Four subjects complained of patello-femoral pain during stimulation, two from each group. Two of these subjects were eliminated from the study; one by themselves and the other by the investigator. The remaining subjects reported no further patello-femoral discomfort.

Two subjects experienced a mild quadriceps femoris muscle strain, one from each group. Both subjects were training at contraction intensities greater than 100% of their MVC. Both individuals were eliminated from the study. This raises the issue of whether or not subjects who acheive contractions in excess of 100% MVC are exceeding the ability to voluntarily activate motor units or the tensile strength limit of muscle and connective tissue or both.

Reports by other investigators show that injuries caused by electrically induced contractions have occurred. These injuries include patella tendonitis [10] , patella-femoral pain[8] , and low back pain.[10] It is unknown whether the type or frequency of injuries caused by training with electrically induced contractions differs from that of training with voluntary contractions.

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FURTHER STUDY

Summary

The purposes of this study were: 1) to determine if muscle contractions induced by PMEF stimulation resulted in greater strength gains than NMES-induced contractions; 2) to assess the difference in pain intensity and quality produced by NMES and PMEF stimulation; and 3) to determine if the two forms of stimulation produced differences in perceived contraction intensity.

Forty-six healthy volunteers (20 male and 26 female, age 19-37 years) participated initially in this study. Subjects were randomly assigned to either a NMES Group (N=21: 9 male; 12 female) or a PMEF Group (N=19: 9 male; 10 female). All subjects were blind to group assignment. Two subjects from the NMES Group and two subjects from the PMEF Group failed to complete the study due to musculoskeletal pain; two subjects were eliminated from the study after the first week because they could not achieve at least 30% of their MVC.

After determining limb dominance, all subjects participated in a familiarization session which consisted of warm-up contractions, maximum voluntary contractions, and electrically induced involuntary contractions of both

quadriceps femoris muscles. All subjects were tested the following day to determine the maximum quadricep femoris muscle torque for both the dominant and control limbs. The NMES and PMEF Groups were then placed on a training protocol of electrically induced quadriceps femoris muscle contractions produced by their respective form of stimulation. All subjects completed 10 induced involuntary contractions per exercise session. Contractions lasted 10 seconds each and were separated by a 50 second rest period. All subjects completed a total of 12 exercise sessions. These sessions were conducted three times a week over a four-week time period. After completing the training protocol, all subjects were tested again to determine the maximum torque of the quadricep femoris muscle. This was done for both the treated and control limbs and conformed to the initial testing session.

Subjects in both groups completed a McGill Pain Questionnaire and VAS for perceived contraction intensity after the initial and final exercise sessions. In addition, eight subjects completed a VAS for pain intensity ratings after every exercise session. The repeated ratings were done to determine the reliability of the 10-cm VAS when measuring pain associated with electrical stimulation over repeated applications. The training contraction intensity and maximum current amplitude for all exercise contractions were recorded for all subjects in both groups.

The statistical significance of results from data analyses were determined at a $p < .05$ level. The torque data from pretest and posttest sessions of both the control and treated limb were analyzed using a three-way analysis of variance for repeated measures. The results of this test showed that: 1) the control and treated limb of both groups had a significant increase in strength; 2) the strength increase of the treated limb was significantly greater than that of the control limb for each group; and 3) the post test strength increases of the control limb and treated limb of both groups were not significantly different from each other. Therefore, both forms of stimulation produced similar strength gains. This result supports the first null hypothesis that NMES and PMEF produce equal strengthening effects.

Pain intensity and quality scores from the initial and final exercise sessions were analyzed with a two-way analysis of variance for repeated measures. The results of this analysis show that pain intensity and quality were not different between the groups, nor did they change over time. This finding indicates that both groups experienced pain of the same intensity and quality during the training study. The scores from the eight subjects who scored a VAS after every exercise session were analyzed with a one way analysis of variance. The mean square values were then used to compute an ICC score. The ICC was .95 and which shows the

VAS to be a reliable instrument when measuring pain caused by electrical stimulation.

Initial and final perceived contraction intensity ratings were also analyzed with a two-way analysis of variance for repeated measures. The results showed that a significant increase in contraction intensity occurred over time, but the interaction of group over time was not significant. The perceived contraction intensity data were then analyzed using an analysis of covariance. This was done because the PMEF Group had a higher initial perceived contraction intensity rating and a difference was found between groups over time. The results of the analysis of covariance showed that the PMEF Group did perceive their induced contractions as being stronger than those experienced by the NMES group. Because a significant difference existed between the actual training intensities of the two groups, the VAS was shown to be a valid instrument for detecting this difference.

The PMEF group trained at a mean training contraction intensity of 70% MVC compared to the 56% MVC level of the NMES group. Results from the one way analysis of variance used to analyze these training contraction intensities show them to be significantly different. The NMES and PMEF Groups had an average maximum current amplitude of 38 mA and 40 mA, respectively. A one way analysis of variance showed that no significant mean difference existed between the maximum current amplitude tolerated by the groups.

The second null hypothesis of this study, that NMES and PMEF stimulation produce equivalent levels of pain and perceived contraction intensity, must be rejected. The pain experienced was the same, but the perceived contraction intensity was not. It must be pointed out, however, that the pain ratings were probably influenced by the different training intensities of the two groups. The more intense muscle contractions of the PMEF Group may have contributed to their pain score. Therefore, the pain score of the PMEF Group may be inflated and not totally attributable to the mode of stimulation. It is not clear why the PMEF Group trained at a higher intensity than the NMES Group. The contraction intensity difference between the groups was not due to a limitation in current output; only four subjects in each group exceeded the capabilities of the electrical stimulator. Measuring pain responses from groups training at equal contraction intensities would help to determine if pain produced by the two forms of stimulation is actually the same.

Conclusions

Within the scope of this study, the following conclusions can be made:

1) NMES and PMEF stimulation can induce involuntary contractions capable of producing significant strength gains in healthy subjects.

2) The gains in strength produced by NMES and PMEF stimulation are not significantly different.
3) PMEF stimulation is capable of producing a higher training contraction intensity than NMES without a concomitant increase in pain intensity and quality.
4) The 10-cm VAS is a reliable instrument for measuring pain produced by NMES and PMEF stimulation. The 10-cm VAS is also a valid instrument for detecting differences in induced muscle contraction intensity of at least 14%.

Recommendations for Further Study

Undesirable noise and heat are produced by magnetic stimulation devices capable of producing tetanic muscle contractions. Further technological advances will be required to eliminate these undesirable effects. While encouraging, the results from trials using magnetic stimulation to strengthen muscles are inconclusive because of their limited number, design, and the output limitations of the magnetic stimulator. Only two investigations other than this one have reported using magnetic stimulation for muscle strengthening purposes.

Further research using PMEF is necessary to determine if it is more advantageous for rehabilitative purposes than NMES. The issue of whether or not PMEF is less painful than NMES is still unresolved. Pain responses measured from groups trained at equal contraction intensities might provide some clarification to this question. It is unknown

how the two forms of stimulation may differ in their effect on strength if applied for longer periods of time. PMEF's effect on other parameters of muscle performance is also not known. These parameters include, but are not limited to: muscle endurance; power; and time to peak torque. Additional investigations comparing NMES and PMEF stimulation on both healthy subjects and subjects with limb pathology are needed.

APPENDIX A

CONSENT FOR RESEARCH STUDY

Muscular Strength Gains and Sensory Perception Changes: A Comparison of Combined Electric/Magnetic and Electric Stimulation.

I, _____, freely and voluntarily agree to participate in a thesis research project under the direction of Robert Wainner, Dr. Arthur Nitz, Dr. Dean Currier, and Dr. Charles Carlson to be conducted at the Health Science Learning Center at the University of Kentucky.

I understand that knowledge of how magnetic and electrical stimulation improves muscle strength is important in developing appropriate rehabilitation programs. The purpose of this study is to evaluate the changes that occur in muscle strength and sensory perception when people have their muscles stimulated with either combined electric/magnetic pulses or electrical pulses.

In agreeing to participate in this study I understand that I will be assigned to one of two treatment groups. One group will receive electric stimulation alone to the knee extensor musculature and the other group combined electric/magnetic stimulation. The two groups will be matched for gender and assigned by chance using a random numbers table. The opposite limb of subjects in both groups will be used as the control measure. All groups will have their knee extensor muscle strength tested twice over a six-week period. I further understand that I will be asked to

attend stimulation sessions three times a week, for four weeks. I understand that the stimulation may be uncomfortable, and that the stimulation will be gradually adjusted to at least 30% of my maximal voluntary contraction as my tolerance allows. The stimulation sessions will last approximately 10-15 minutes. During this time I will be receiving 10 second bouts of stimulation followed by 50 seconds of rest. This will be repeated **ten** times each session. I also understand that I will be asked to rate my level of comfort concerning the stimulation and the muscle contraction each session.

I understand that review of the literature and experience of the researchers indicate the following risks: possibly muscle soreness that lasts for about three days; possible electric shock; and possible thermal burns due to prolonged use of the magnetic coil. To minimize subject risk, all equipment is UL safety rated and subjects will be insulated from the magnetic coil with four layers of toweling. I also understand I am to expect no benefit or gain from my participation in this study.

I understand that participation is voluntary; refusal to participate will involve no penalty of loss of benefits to which I am otherwise entitled. I understand that no compensation is being offered or is available for my participation.

I understand that in the event of physical injury resulting from this research project in which I am

participating, no form of compensation is available. Medical treatment may be provided at my own expense or at the expense of my health care insurer. I also understand that if I desire further information about this matter, I should contact Robert Wainner, PT, at 548-2459.

I authorize Robert Wainner, the Department of Clinical Sciences, and the Division of Physical Therapy to keep, preserve, use and dispose of the findings from this research with the provision that my name will not be associated with any of the results.

I have been given the right to ask, and have answered, any questions concerning the procedures to be used during this research. Questions have been answered to my satisfaction. I understand that my confidentiality and anonymity will be protected. I further understand that I have the right to terminate my involvement in this project at any time, without sustaining any form of penalty. I have read and understand the contents of this form and have received a copy.

_____ _____

Witness Date Participant Date

I have explained and defined in detail the research procedure to which the subject has consented to participate.

_____

Signature Date

APPENDIX B

NO INTENSITY ——————————————— MAXIMUM INTENSITY

SHORT-FORM McGILL PAIN QUESTIONNAIRE SF-MPQ

RONALD MELZACK

PATIENT'S NAME_____ DATE_____

	NONE	MILD	MODERATE	SEVERE
THROBBING	0)_____	1)_____	2)_____	3)_____
SHOOTING	0)_____	1)_____	2)_____	3)_____
STABBING	0)_____	1)_____	2)_____	3)_____
SHARP	0)_____	1)_____	2)_____	3)_____
CRAMPING	0)_____	1)_____	2)_____	3)_____
GNAWING	0)_____	1)_____	2)_____	3)_____
HOT-BURNING	0)_____	1)_____	2)_____	3)_____
ACHING	0)_____	1)_____	2)_____	3)_____
HEAVY	0)_____	1)_____	2)_____	3)_____
TENDER	0)_____	1)_____	2)_____	3)_____
SPLITTING	0)_____	1)_____	2)_____	3)_____
TIRING-EXHAUSTING	0)_____	1)_____	2)_____	3)_____
SICKENING	0)_____	1)_____	2)_____	3)_____
FEARFUL	0)_____	1)_____	2)_____	3)_____
PUNISHING-CRUEL	0)_____	1)_____	2)_____	3)_____

PPI

0) NO PAIN _____

1) MILD _____

2) DISCOMFORTING _____

3) DISTRESSING _____

4) HORRIBLE _____

5) EXCRUCIATING _____

NO PAIN _____ WORST POSSIBLE PAIN

APPENDIX C

MUSCULAR STRENGTH GAINS AND SENSORY PERCEPTION CHANGES; A COMPARISON OF ELECTRICAL AND COMBINED ELECTRICAL/MAGNETIC STIMULATION

BY ROBERT S. WAINNER

Investigations have been conducted to assess the ability of neuromuscular electrical stimulation (NMES) to induce strength gains (increase torque) in healthy subjects. However, a negative aspect of NMES is that it causes pain[16] and cramping sensations[8] when applied at amplitudes required to produce a strengthening effect.

Recent work using weak static and pulsed magnetic fields to diminish pain arising from musculoskeletal structures has been reported.[62, 63, 64, 70,71] Inflammatory disorders, open wounds, and diagnostic testing also have received magnetic stimulation[17].

A new device, the modified Cadwell MES-10 (MES-10 modified, Cadwell Laboratories, 909 N. Kellogg Street, Kennewick, Washington, 99336), has been developed that induces an electrical current by means of a pulsed magnetic field. This technological advance allows study of effect of magnetic stimulation on strength development.

The ability of time varying (pulsed) electromagnetic fields to induce a skeletal muscle contraction in both animal and human subjects is documented.[58, 59, 21]

The induced muscle contraction is actually the result of an induced electrical current in accordance with Faraday's law

which states that whenever a magnetic field changes there is an induced electric field that impedes the changing magnetic field.[18] Magnetic stimulators accomplish this by passing electrical current through a coil which in turn creates a pulsed magnetic field. The pulsed magnetic field in turn, produces an induced electric field within it.[60] The amplitude of the magnetic field, or flux density, is measured in teslas (T) or gauss (g) (10,000 g = 1 T).

If a conducting medium such as human tissue lies within the induced electrical field, current will flow through the tissue but in the opposite direction of current flowing through the coil and as a pulsed cosine waveform. If the induced current density is of sufficient amplitude and duration, neuromuscular tissue will be depolarized the same way as if electrodes had been used to transmit the current.[18]

Nervous tissue does not respond to the magnetic field itself but rather to the induced electrical current created by it. An electromagnetic coil acts as an electrode to generate the magnetic field, producing in turn an induced electric current.

Magnetic stimulation has both advantages and disadvantages when compared to NMES. Advantages of magnetic stimulation include: 1) the induced electric current is not attenuated by body tissue (even high resistance structures such as bone); 2) the ability to stimulate deep structure such as the brain, brachial plexus, and lumbar roots with

little or no pain; while disadvantages include: 1) stimulation units are heavy and bulky; 2) stimulation at muscle contractile rates causes the coil to heat and produce loud noise.[60]

Magnetic stimulation can produce strong, relatively pain free muscle contractions in healthy subjects but does so with great variability, 8 to 82% of maximal voluntary contraction.[17] The electric current induced by magnetic stimulation occurs deep within the tissue stimulated and is undiminished by skin impedance.[18] As a result, large diameter motor nerve fibers are stimulated while the smaller diameter pain fibers are not.[19]

When conventional NMES is combined with magnetic stimulation an augmented response occurs. Subjects receiving combined electrical/magnetic stimulation (PMEF) produce a stronger muscle contraction which is less painful compared with subjects receiving conventional NMES alone.[17,20] The limited research conducted to date has not shown magnetic stimulation alone to be effective in producing strength gains in healthy subjects or patients recovering from surgery.[21,22] There has only been one study to date comparing conventional NMES to PMEF. Currier et al. found that PMEF was 50% less painful and more effective than conventional NMES preventing limb atrophy in patients recovering from anterior cruciate ligament reconstruction. Both groups demonstrated significant strength gains from pretest levels when tested six weeks after surgery.[22]

The purpose of this study was to see if combining NMES with magnetic stimulation produces greater strength gains with less pain and perceived contraction intensity than is achieved by NMES alone.

METHOD

Subjects

Forty healthy volunteers completed the training protocol for this study. After being informed of the experimental protocol and risks involved with the training procedure, all subjects signed the consent form before participating in this project. All subjects were in a good state of health, had no prior history of knee surgery or presented lower limb pathology, and had no nervous system disease. Table 1 presents the descriptive statistics for the subjects' age, height and weight.

Subjects were randomly assigned to either a NMES Group or a PMEF Group for treatment of the dominant limb. The dominant limb was identified as the limb subjects used to kick a stationary ball. All subjects were blind to group assignment and the non-dominant limb of each subject was used as the control measure.

Procedure

Familiarization and Pretest. Familiarization sessions utilizing the Cybex II dynamometer (CYBEX, Division of Lumex, Inc, 2100 Smithtown Ave., Ronkonkima, NY 11779) were conducted on the treated and control limbs the day prior to

the pretest procedure. These sessions were administered to prevent any torque changes due to lack of familiarity with the equipment or training procedure, and to decrease any apprehension of induced stimulation.

Beginning with the control limb (non-dominant limb), subjects were seated and secured on the Cybex II dynamometer chair with the hip and knee angles positioned in 60^0 of flexion. This position has been shown to be reliable for obtaining maximum torque values.[50] The dynamometer's axis of rotation was aligned with the anatomical axis of the knee being tested and the speed was set at 0^0/sec. The opposite limb was allowed to hang unconstrained over the edge of the seat and subjects grasped the seat handles during contractions. Each subject then completed six voluntary (three warm up then three maximum) contractions. Warm up contractions were held for two seconds each and maximum voluntary contractions were held for five seconds each . The same procedure was then followed for the limb to be treated (dominant limb). In addition, the dominant limb completed three NMES contractions induced for five seconds each; all contractions were separated by an one minute rest period.

The following day, subjects were positioned on the Cybex II dynamometer identically as in the familiarization sessions and tested for maximum voluntary isometric torque production of both limbs. Beginning with the dominant limb subjects performed three submaximal warm up contractions

(held two-seconds each) followed by three maximum voluntary contractions. Each maximum voluntary contraction was separated by a two minute rest period. The opposite limb was allowed to hang unconstrained over the edge of the seat and subjects grasped the chair handles while maximum verbal encouragement was given during contractions. The same procedure was then repeated for the control limb. Responses were recorded on a duel channel recorder (damp setting at 2). The highest peak torque score (N.m) of the three trials was used as the subjects pretest MVC score.

Training and Posttest. After being positioned as previously described, water soaked sponges and carbon rubber electrodes (8 x 12.5) were attached to the subject's dominant thigh. One stimulating electrode was placed on the subject's skin over the femoral nerve at the femoral triangle in a vertical fashion. The other identical electrode was placed over the midportion of the vastus medialis muscle in a vertical fashion. Both electrodes were held firmly in place by velcro straps applied circumferentialy. Four layers of toweling were applied over the thigh and electrodes, on top of which was applied the large magnetic stimulation coil (26 cm diameter). Two velcro straps were applied in a circumferential fashion to hold the stimulation coil in place.

The Electrostim 180-2i (Electrostim 180-2i, Elecrostim USA LTD, PO Box 3425 Joliet, IL, 60435) was used to provide the electrical stimuli applied to subjects in this study. The stimuli consisted of 0.1 msec sinewaves at a carrier frequency of 2,500 Hz and delivered at 50 bursts per second. The modified MES-10 magnetic stimulator equipped with the large coil was used to induce an electrical current flow in the tissuesof the PMEF subjects. The cosine waveform pulse duration was 240 microseconds, with a rise time of 30 microseconds. This stimulus was repeated at 60 pps. The coil was applied over the subjects' electrodes in both the NMES and PMEF Groups but was only activated for PMEF subjects.

With the NMES and magnetic stimulators concealed behind a curtain, NMES current amplitude was adjusted manually to maximal subject tolerance during the first contraction. Because the stimulators were concealed, subjects were verbally notified five seconds prior to the onset of stimulation. For NMES subjects, once a muscle contraction intensity of 30% MVC was achieved, a tape recording of the noise produced by the magnetic stimulator was manually activated. The recorded noise was activated concomitantly with the electric stimulation and administered during all subsequent contractions. PMEF subjects received magnetic stimulation once a muscle contraction of 30% MVC had been obtained. To account for current accommodation, stimulus

tolerance after the first three seconds of each exercise contraction. Once PMEF subjects received maximum magnetic stimulator amplitude, the amplitude of the electrical stimulation was increased. Subjects unable to tolerate an involuntary muscle contraction intensity of 30% MVC were eliminated from this study.

The NMES and PMEF Groups were started on stimulation exercise sessions the week following (3-4 days) their MVC torque testing. The sessions (utilizing involuntary induced contractions) were conducted three times per week for a total of four weeks. An exercise session consisted of ten, ten-second stimulation contractions, with each contraction separated by a 50-second rest period. The training contraction intensity (expressed as a percentage of the pretest MVC) and maximum electrical current amplitude was recorded for all exercise contractions for all subjects. Subjects in each group had received a total of 120 induced contractions at the end of the four-week experimental period.

Following the initial and final exercise sessions, all subjects were administered a McGill Pain Questionnaire (short form). This questionnaire consists of ratio (10-cm visual analog scale (VAS) and interval level (Present Pain Index (PPI)) scales to measure pain intensity. It also lists 11 words describing pain qualities as sensory and 4 words as affective. A 10-cm (VAS) was also used for subjects to rate the intensity of the induced contractions.

In addition, eight subjects were randomly chosen to rate their pain with a 10-cm VAS after every exercise session to assess the reliability of the VAS when measuring pain associated by electrical stimulation.

Following the four-week training period, all subjects had both limbs retested for maximum voluntary torque in a manner identical to the pretesting session.

Data Analysis. A three-way analysis of variance (ANOVA) for repeated measures (treated limb, control limb, and group) was used to analyze the torque changes between the groups. No significant difference in pre-test torque was found. A two-way analysis of variance for repeated measures (Group and Time) was used to analyze the differences in perceived pain intensity, pain quality, and perceived contraction intensity between the groups. Because the difference in pre-treatment perceived contraction intensity showed a trend toward significance, these data were subsequently analyzed with a two way analysis of covariance with the pre-treatment perceived contraction intensity used as the covariate. A one-way analysis of variance and intraclass correlation coefficient (ICC) was used to determine the reliability of the 10-cm VAS. The differences in mean training contraction intensity and mean electric current intensity between the two groups were analyzed with a one-way ANOVA. A probability level of .05 was used to determine significance in all ANOVA analyses.

RESULTS

Torque. Table 3 is a summary of the three-way ANOVA for repeated measures used to analyze mean torques of the treated and control limbs of both groups. Both the NMES and PMEF Groups demonstrated statistically significant treated limb strength gains of 13% and 17%, respectively. There was also a 6% strength increase for the control limbs of both groups that was statistically significant. The interaction of group by treated limb showed no statistically significant differences in torque gain between the groups. The strength increases along with the mean training contraction intensity of each group is depicted in Figure 1.

Posttest Torque Gain There was no significant difference in torque gains between the groups at posttest for either the treated or control limb.

Sensory Perception Changes. Eight subjects rated their pain after every exercise session using a 10-cm VAS. The ICC of .95 indicates that the 10-cm scale is a very reliable instrument when measuring pain caused by electrical stimulation.The descriptive statistics for initial, final, and change scores for the VAS are presented in Table 4. Results of these data and the scores from the PPI are summarized in Tables 5 and 8. There was no statistically significant difference between the groups for either the 10-cm VAS or PPI. Even though both groups tolerated progressively higher current amplitudes in every exercise session, there was no significant increase in pain over time

for either group. Figure 2 graphs the mean current amplitudes of each group by exercise session. The interaction of group by time was not statistically significant for either the 10-cm VAS or PPI pain intensity ratings.

The descriptive statistics for the initial, final, and change scores of the perceived contraction intensity ratings are presented in Table 15. The PMEF group rated the contractions of their initial and final exercise session as being more intense than the contractions experienced by the NMES group ($F= 4.54$; 1,37 df). The PMEF Group's training contraction intensity was 14% greater than the NMES Group's and is statistically significant ($F= 7.89$; 1,38 df).

The number of sensory, affective, and total number of pain descriptors chosen by both groups were nearly identical. No significant differences existed between the groups, or over time, or for the group by time interaction.

Figure 2 graphically contrasts the mean training contraction intensities and maximum current amplitudes of both groups by exercise session. Figure 3 graphically contrasts the mean training contraction intensities of both groups by week.

Adverse Effects. Several subjects reported muscle soreness in the treated limb after the first exercise session. This soreness resolved after the second or third exercise session.

One subject in the NMES group experienced a 12% and 5% torque decrease in the treated and control limb, respectively, after completing the training regimen. No one in the PMEF group experienced a torque decrease.

Also, two subjects from each group complained of patello-femoral pain; one subject from each group was eliminated from the study because their pain did not resolve. One subject from each group incurred a mild strain of the quadriceps femoris muscle. The strains occurred in the seventh and twelfth exercise session during contractions in excess of 100% of the subjects MVC. Both of these subjects were eliminated from the study.

DISCUSSION

Torque. The treated limbs of the NMES and the PMEF groups demonstrated a 14% and 17% strength increase, respectively, after the four-week training period. The occurrence of an increase in strength following a regimen of electrical induced contractions is consistent with previous findings of other investigators.[6-15]

Two measures were taken to ensure that strength increases were due solely to the mode of stimulation and not confounded by external influences. First, all subjects were blind to group assignment to prevent PMEF subjects knowing that they were receiving two forms of stimulation rather than one. Second, a tape recording of the noise made by the magnetic stimulator was played during every exercise contraction for NMES subjects to simulate PMEF conditions.

magnetic stimulator was played during every exercise contraction for NMES subjects to simulate PMEF conditions.

Both verbal suggestion and loud noise have been shown to increase peak torque between consecutive tests of a single testing session.[87] Theoretically, this sudden increase in strength unrelated to training is the result of disinhibitory or excitatory influences on the central nervous system. The influence of the noise produced by the magnetic stimulator on torque was not assessed in this study. If an an effect did occur, it's influence on group outcomes should have been equal as both groups were subjected to the same auditory stimuli.

Training Intensity, Although Selkowitz reported a correlation of r= .61 between training intensity and strength gain,[9] the strength gain of the PMEF group's treated limb, though greater, was not significantly different than the gain of the NMES group. The literature reports trials inducing electrical contractions where groups trained with intensity differences ranging from 45%[11] to 50%[10], yet show no difference in strength gain. This result was in spite of the fact that the PMEF group trained at a significantly higher training contraction intensity (70%) than did the NMES group (56%). The precise role training intensity plays in the development of isometric strength is still open to question and warrants further study.

The control limb of both groups demonstrated a 6% increase in strength that was significant. The phenomenon

of a strength increase in the untreated limb is often called a "cross-education" effect. This cross-education effect has been demonstrated in other studies involving voluntary[95, 96, 7] as well as electrically induced contractions.[11, 97] and ranges from 10% - 30%.

There are several possible explanations for the strength increase demonstrated in the control limb but the most probable explanation is that of a centrally mediated neural adaptation.[98] This would be consistent with the fact that early strength gains of the treated limb are primarily due to neural mediated factors.[94]

Training contraction intensity and maximum current amplitude, though not main variables, were analyzed to provide insight into any differences that might exist between NMES and PMEF stimulation. All subjects in the PMEF group were receiving the maximum output of the magnetic stimulator by the second exercise session.

Since the electric current amplitude received by the NMES and PMEF groups was essentially the same, the difference in the PMEF group training contraction intensity must be attributed to the magnetic stimulation. The difference in contraction intensity may simply be a result of the PMEF group receiving an additional source of stimulation. Another explanation is that the magnetic stimulation augmented the electrical current received by the PMEF group. Kellogg reported a mean augmentation effect for torque to occur when magnetic stimulation was combined with

maximally tolerated electrical stimulation. The resulting difference in torque produced by the PMEF stimulation and maximum electrical stimulation alone was 14%[17]. This is precisely the difference between the two stimulation groups in this study.

Sensory Perception Changes. Huskisson have demonstrated that the 10-cm VAS is a valid and reliable tool for measuring pain.[86] Clinically, many subjects describe pain caused by electrical stimulation as being different from pain they experience from other nociceptive stimuli. Since transcutaneous electrical nerve stimulation can cause altered sensory perception and is often used clinically to diminish pain, it was necessary to assess the reliability of the 10-cm VAS when measuring pain caused by electrical stimulation. An ICC of .95 shows the 10-cm VAS to be reliable when measuring pain caused by electrical stimulation.

The scores from the 10-cm VAS and PPI both showed that pain intensity was mild to moderate for both groups and did not significantly increase over time for either group. This was in spite of the fact that both groups progressively increased the amount of electrical current received during training.

Kellogg found that subjects receiving NMES had higher pain ratings than subjects receiving magnetic stimulation only.[21] He mentioned that this was possibly related to the limited output capabilities of the magnetic stimulator,

which prevented a progressive increase in current amplitude as experienced by the NMES group. Kellogg also found that pain increased over time for subjects receiving NMES. A pain increase for NMES group subjects was not found in this study.

Currier et al found that patients recovering from ACL ligament reconstruction rated PMEF stimulation a being 50% less painful than NMES.[22] The use of a cross-over design and post-surgical subjects by Currier however, prevent a valid comparison of the results from his study and this one. The findings of this study do not support one type of stimulation as being more comfortable than the other.

Because the PMEF group demonstrated a higher training intensity, there might possibly be a pain contribution from the muscular contraction in addition to the cutaneous discomfort caused by NMES. Selkowitz and Boutelle have reported that subjects trained with electrical stimulation complained of pain perceived to be from the induced muscle contraction.[8, 9] Kramer has mentioned that a variety of factors, including electrode size and positioning, skin moisture content, and psychological profile can alter the degree to which the electrical stimulus and resultant contraction are perceived as uncomfortable.[42]

Controlling the contraction intensities of subjects receiving NMES and PMEF would allow a more valid comparison of the pain associated with each type of stimulation. Because of the unequal training contraction intensities of

the two groups, the question of whether or not PMEF stimulation is more comfortable than NMES remains unresolved.

There was no difference in the number of sensory or affective pain descriptors reported by either group. Therefore, the quality of pain experienced by the groups was the same and remained unchanged over time. No consistent pattern was seen which indicated that sensory or affective descriptors were most frequently chosen. Because of this inconsistency, no attempt was made to categorize or analyze the data in this manner.

The perceived contraction intensity ratings of the PMEF group at posttesting were significantly higher than those reported by the NMES group. The fact that the PMEF group actually trained at a significantly higher training intensity shows the 10-cm VAS to be a valid tool for measuring perceived contraction intensity. Caution should be exercised when using this scale to detect small differences between groups. The PMEF group demonstrated a training intensity 14% greater than that of the NMES group which is a rather large difference.

Adverse Effects. In addition to mild pain from stimulation, most subjects experienced muscle soreness that resolved after the first week of training. This has occurred in numerous other studies employing electrically induced contractions[6,8,9,11,15,21,52] and is observed when training with volitional contractions also.

The one NMES subject who demonstrated a large torque decrease reported that her activities had not changed over the four week training period. There are other reports in which a few individual subjects show a decrease in torque after training with electrically induced[21] and voluntary contractions.[12] It is unclear how often a strength decrement occurs with NMES training because not all investigations report their data for individual subjects. The extent to which electrical stimulation was responsible for the decrease in strength experienced by this subject is unclear. It not known whether electrical stimulation produces a detrimental effect on strength for predisposed individuals. Further research is need to answer this concern.

Four subjects complained of patello-femoral pain during stimulation, two from each group. Two of these subjects were eliminated from the study; one by themselves and the other by the investigator. The remaining subjects reported no further patello-femoral discomfort.

Two subjects experienced a mild quadriceps femoris strain, one from each group. Both subjects were training at contraction intensities greater than 100% of their MVC. Both individuals were eliminated from the study. This raises the issue of whether or not subjects who achieve contractions in excess of 100% MVC are exceeding psychologic (ability to voluntarily activate motor units) and/or

physiologic limitations (exceeding the tensile strength of muscle and connective tissue).

Reports by other investigators show that injuries due to electrically induced contractions can and do occur. These injuries include patella tendonitis [10] , patella-femoral pain[8] , and low back pain.[10] It is unknown whether the type or frequency of injuries caused by training with electrically induced contractions differs from that of training with voluntary contractions.

CONCLUSION

Within the scope of this study, the following conclusions can be made: 1) NMES and PMEF stimulation can induce involuntary contractions capable of producing significant strength gains in healthy subjects; 2) The gains in strength produced by NMES and PMEF stimulation are not significantly different; 3) PMEF stimulation is capable of producing a higher training contraction intensity than NMES without a concomitant increase in pain intensity and quality; 4) The 10-cm VAS is a reliable instrument for measuring pain produced by NMES and PMEF stimulation. The 10-cm VAS is also a valid instrument for detecting differences in induced muscle contraction intensity of at least 14%.

APPENDIX D

TORQUE DATA

	NMES			
	Pre-test		Post-test	
Subject	Dominant	Control.	Dominant	Control
1	244.08	231.88	292.90	244.08
2	223.74	216.96	252.22	240.01
3	150.52	130.18	195.26	187.13
4	222.38	253.57	280.69	257.64
5	244.08	199.33	244.08	244.08
6	282.05	292.90	284.76	288.83
7	160.01	158.65	169.50	160.01
8	191.20	158.65	168.14	150.52
9	313.24	296.96	325.44	317.30
10	225.10	242.72	244.08	231.88
11	153.23	146.45	158.65	138.31
12	301.03	317.30	340.36	341.71
13	235.94	244.08	252.22	231.88
14	252.22	219.67	341.71	246.79
15	149.16	117.97	178.99	147.80
16	127.46	112.55	131.53	113.90
17	105.77	109.84	119.33	111.19
18	191.20	154.58	189.84	162.72
19	162.72	149.16	172.21	142.38
20	174.92	155.94	252.22	160.01
21	166.79	165.43	204.76	176.28

TORQUE DATA

	PMEF			
	Pre-test		Post-test	
Subject	Dominant	Control.	Dominant	Control
1	86.78	78.65	131.53	103.06
2	189.84	200.69	197.98	223.74
3	233.23	211.54	249.50	235.94
4	138.31	149.16	162.72	170.86
5	233.23	187.13	272.56	207.47
6	170.86	146.45	170.86	157.20
7	109.84	122.04	120.68	113.90
8	260.35	276.62	357.98	276.62
9	268.49	305.10	317.30	291.54
10	207.47	185.77	284.76	227.81
11	154.58	142.38	174.92	146.45
12	214.25	241.39	307.81	260.35
13	329.51	343.07	349.85	328.15
14	225.10	230.52	229.16	215.60
15	225.10	189.84	264.42	215.60
16	164.08	166.79	183.06	188.48
17	146.45	132.89	154.58	130.18
18	166.79	173.57	180.35	170.86
19	122.04	117.97	130.18	119.33

NMES PAIN INTENSITY RATINGS

	10cm pain			10cm Cx Int.			PPI		
Subject	Pre	Post	Diff	Pre	Post	Diff	Pre	Post	Diff
1	1.6	3.8	2.2	6.3	6.9	0.6	1	2	1
2	2.0	2.0	0.0	2.1	3.9	1.8	2	2	0
3	3.6	8.1	4.5	8.8	6.9	-1.9	2	4	2
4	2.0	2.4	0.4	3.1	6.7	3.6	0	1	1
5	1.3	1.5	0.2	5.0	3.4	-1.6	1	1	0
6	2.5	5.5	3.0	5.8	6.3	0.5	1	1	0
7	3.5	2.8	-0.7	3.7	4.1	0.4	2	2	0
8	0.9	1.7	0.8	9.9	8.8	-1.1	1	2	1
9	0.5	0.5	0.0	7.8	9.7	1.9	1	1	0
10	1.8	0.2	-1.6	7.8	1.1	-6.7	2	0	-2
11	2.6	2.8	0.2	4.4	4.6	0.2	2	2	0
12	2.0	3.2	1.2	6.7	9.6	2.9	2	2	0
13	5.3	7.6	2.3	7.2	6.7	-0.5	2	3	1
14	7.2	1.6	-5.5	7.2	7.6	0.4	3	1	-2
15	3.4	2.7	-0.7	3.7	3.5	-0.2	1	1	0
16	1.2	1.7	0.5	8.8	8.0	-0.8	1	2	1
17	0.7	0.6	-0.1	6.0	8.6	2.6	0	0	0
18	3.8	8.7	4.9	8.0	9.5	1.5	2	3	1
19	7.0	5.5	-1.5	8.5	8.6	0.1	3	3	0
20	3.1	4.8	1.7	3.1	5.7	2.6	1	2	1
21	2.2	4.2	2.0	6.1	6.9	0.8	2	2	0

NMES PAIN QUALITY RATINGS

	Sensory			Affective			Total		
Subject	Pre	Post	Diff	Pre	Post	Diff	Pre	Post	Diff
1	1	4	3	0	1	1	1	5	4
2	4	4	0	1	0	-1	5	4	-1
3	5	13	8	2	2	0	7	15	8
4	1	3	2	1	0	-1	2	3	1
5	0	2	2	1	0	-1	1	2	1
6	4	5	1	0	0	0	4	5	1
7	6	8	2	0	0	0	6	8	2
8	1	1	0	0	0	0	1	1	0
9	3	2	-1	1	0	-1	4	2	-2
10	2	3	1	2	2	0	4	5	1
11	3	8	5	1	2	1	4	10	6
12	4	5	1	0	0	0	4	5	1
13	6	13	7	1	2	1	7	15	8
14	12	5	-7	5	6	1	17	11	-6
15	6	3	-3	0	0	0	6	3	-3
16	1	1	0	0	0	0	1	1	0
17	2	1	-1	0	1	1	2	2	0
18	4	8	4	5	1	-1	6	9	3
19	3	3	0	5	3	1	5	6	1
20	2	2	0	0	3	3	2	5	3
21	3	3	0	0	0	0	3	3	0

PMEF PAIN INTENSITY RATINGS

	10cm pain			10cm Cx Int.			PPI		
Subject	Pre	Post	Diff	Pre	Post	Diff	Pre	Post	Diff
1	2.8	6.5	3.7	9.0	8.6	-0.4	1	2	1
2	4.0	5.7	1.7	8.1	9.8	1.7	2	2	0
3	5.0	7.0	0.2	7.2	8.1	0.9	2	2	0
4	2.9	2.4	-0.5	7.5	8.2	.07	1	2	1
5	6.0	2.0	-4.0	8.3	6.8	-1.5	3	1	-2
6	3.5	5.3	1.8	3.4	6.8	3.7	2	3	1
7	2.5	5.9	3.4	3.9	7.5	3.6	1	2	1
8	1.8	1.9	0.1	7.3	8.3	1.0	1	1	0
9	1.5	2.2	0.7	7.7	9.2	1.5	1	1	0
10	4.7	2.5	-2.2	6.6	8.3	1.7	2	1	-1
11	0.0	0.2	0.2	6.6	8.3	1.7	0	1	1
12	2.1	0.0	-2.1	7.9	8.6	0.7	0	0	0
13	4.8	3.3	-1.5	6.7	9.2	2.5	2	2	0
14	2.7	3.9	1.2	2.9	3.4	0.5	1	1	0
15	0.3	2.3	2.0	9.1	8.2	-0.9	0	2	2
16	2.4	3.4	1.0	3.2	6.5	3.3	2	2	0
17	4.8	5.2	0.4	6.3	7.4	1.1	2	2	0
18	7.2	6.8	-.04	8.1	8.9	0.8	3	2	-1
19	3.0	3.9	0.9	8.5	8.5	0.0	2	2	0

PMEF PAIN QUALITY QUALITY RATINGS

	Sensory			Affective			Total		
Subject	Pre	Post	Diff	Pre	Post	Diff	Pre	Post	Diff
1	1	6	5	0	0	0	1	6	5
2	6	12	6	1	2	1	7	14	7
3	5	7	2	3	3	0	8	10	2
4	3	2	-1	1	0	-1	4	2	-2
5	6	2	-4	2	0	-2	8	2	-6
6	9	10	1	1	3	2	10	13	3
7	2	5	3	3	2	-1	5	7	2
8	2	1	-1	0	0	0	2	1	-1
9	9	7	-2	1	1	0	10	8	-2
10	2	0	-2	0	0	0	2	0	-2
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
13	11	7	-4	3	3	0	14	10	-4
14	2	5	3	0	1	1	2	6	4
15	0	3	3	0	0	0	0	3	3
16	4	1	-3	0	0	0	4	1	-3
17	5	3	-2	1	2	1	6	5	-1
18	10	4	-6	7	4	-3	17	8	-9
19	1	2	1	2	1	-1	3	3	0

REPEATED 10-cm VAS PAIN RATINGS

	Subject							
	1	2	3	4	5	6	7	8
Exercise Session								
1	3.0	2.1	2.4	1.4	2.2	3.0	2.0	3.3
2	2.6	2.7	3.6	3.9	4.6	6.2	4.6	7.0
3	1.2	1.6	4.9	4.3	5.3	7.1	2.5	7.7
4	1.6	0.4	3.5	4.3	5.2	7.6	2.0	9.3
5	1.6	0.4	4.7	3.7	5.3	5.8	0.6	7.6
6	0.7	0.3	3.5	4.5	3.7	5.8	2.9	7.6
7	2.4	0.0	3.6	3.4	4.0	5.7	2.4	7.1
8	2.7	0.0	3.4	3.7	3.7	5.1	2.4	7.1
9	2.3	0.0	3.3	4.2	4.1	4.8	2.6	7.3
10	3.0	0.0	3.7	3.8	3.9	5.6	2.9	7.7
11	2.0	0.0	3.2	3.7	3.9	4.4	2.3	6.6
12	2.7	0.0	3.2	3.9	4.2	5.5	3.2	7.1

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